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The McGregor Spectrograph of the McMath-Hulbert Observatory*

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INTRODUCTION

THE McGregor spectrograph of the McMath-Hulbert Observatory of the University of Michigan was designed and constructed by Dr. Robert R. McMath, Director of the Observatory, as a part in the development of a program of solar observation made possible by a grant from McGregor Fund of Detroit. Installation, adjustment, and testing of the instrument have been carried out by the writer.

The solar observation program has, as its two most important tenets, the requirements that as many variables as possible pertaining to a disturbance on the sun be recorded, and that the records be concurrent. Thus, if a sunspot is under observation, positions of the spot and its structure, motions along the line of sight from the observer to the spot, measures of associated magnetic fields, changes in the brightness of the light emitted at different points in the spot and in different wave-lengths—all are variables that should be recorded concurrently; for only in this way can one secure unambiguous, homogeneous data.

In the fifty-foot tower of the McMath-Hulbert Observatory there are instruments that have been described elsewhere in great detail,[1] for photographing the sun in monochromatic light and for determining the radial velocity at any, or all, points of the sun. All observations are in the form of photographs on thirty-five millimeter motion picture film with an accompanying accurate time record. With the films resulting from the use of this equipment, a complete and continuous determination of the motion, in three orthogonal directions, of any part of the sun can be carried on.[2] An obvious and important datum to supplement such measures of the motions in the trajectories of solar disturbances is a continuous, concurrent registration of variations in their brightness. It is the function of the McGregor spectrograph to operate simultaneously with our older equipment to supply hitherto lacking observations of light intensity.

GENERAL CONSTRUCTION

Essentially, the McGregor spectrograph is a modified form of spectroheliograph, employing a plane grating and lens in a Littrow type mounting as the spectrographic element. It occupies a darkroom, ten by thirty-eight feet in plan, and twelve feet in height, in the McGregor Building of the observatory. The spectrograph rests on two concrete piers, twenty-five feet apart, that are independent of the building and of each other. They are of such a height, and so aligned for architectural reasons, that the line joining the first slit to the lens is horizontal, six feet above the floor level, bearing sixteen degrees east of north. Sunlight is brought to this level and directed northward along the

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slit-lens line by the three plane mirrors of the McGregor Tower telescope. The first plane mirror is a coelostat mirror of fused quartz (eighteen inches aperture, cast by the Thermal Syndicate Company) located near the top of the tower, sixty feet above the floor level. The second plane is an auxiliary mirror that directs the beam of light reflected from the coelostat mirror vertically downward through a lens. It is a Pyrex disk, of ribbed construction, sixteen inches in aperture. The third plane mirror (aperture eleven inches, cast by the Thermal Syndicate of fused quartz) is located near the bottom of the tower to receive the light reflected downward from the second plane and turn the beam horizontally northward to the spectrograph. Lenses of different focal lengths, to provide solar images of varying sizes, can be inserted in the beam at several points between the slit of the spectrograph and the coelostat mirror. The three plane mirrors in the McGregor Tower telescope and the lens in the spectrograph were all figured by the Perkin-Elmer Corporation.

The spectrograph lens has a clear aperture of six inches. Schott glasses DK7 and F2 were used for the crown and flint components, respectively. The minimum focal length at 4860A is 7580 millimeters. It acts as collimator and telescope lens for a plane speculum metal grating. The grating was ruled with 600 lines per millimeter over an area of 115 by 100 millimeters on the ruling engine of the University of Chicago. After ruling, the grating was aluminized. The grating concentrates the diffracted light in the general direction of 6563A in one of the first orders. Photographic tests show that it places more than twice as much light in this spectral region as the best of six other gratings. The combination of grating and lens yields a dispersion of 2.2 angstroms per millimeter at the minimum focal length.

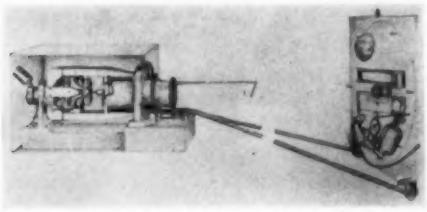

FIG. 1. General view of the McGregor spectrograph (sketch by Miss Caroline A. Lee).

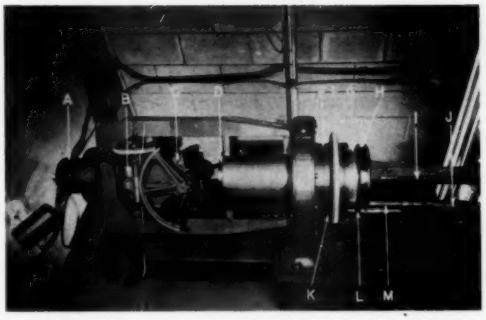

FIG. 2a. The grating and lens unit.

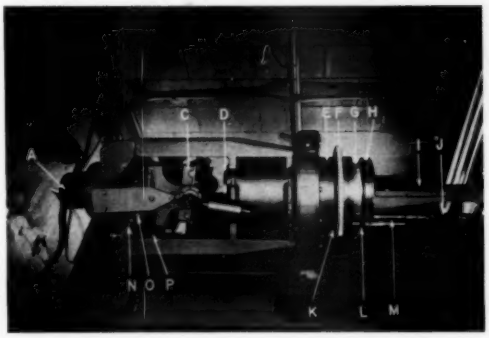

FIG. 2b. The grating and lens unit.

An unusual form of mounting was designed for the grating and lens, and for the spectrograph head that carries the slits and slit mechanisms, in order that certain types of solar observation would be made easier. In some cases observations are made with the spectrograph slit tangential to the limb of the sun, but equally often observations must be made with the slit perpendicular to the limb. Hence, the spectrograph must be rotatable through 360 degrees. In the McGregor spectrograph either the grating-lens unit, or the spectrograph head can be rotated through a complete revolution independently of the other. Some advantages of this type of construction are the possibility of changing either spectrograph head, or grating-lens unit without disturbing the other, and absence of changes in flexure with angle of rotation that would be present in a rigid connection such as a tube

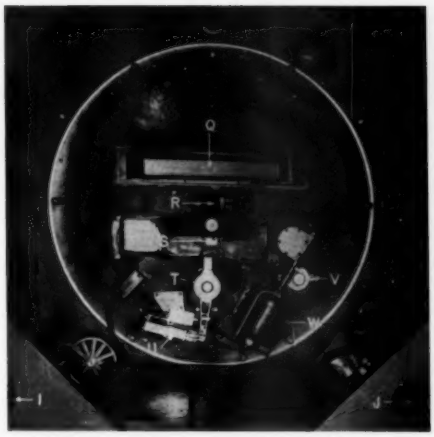

FIG. 3a. The spectrograph head, viewed from the grating.

FIG. 3b. The spectrograph head, viewed from the observer's station.

running from the head to the grating and lens. Since the dispersed beam from the grating is returned off the axis of rotation to the spectrograph head, several different receivers for this radiation can be set up on the head and brought into position for use by rotation of either head or grating, to suit the convenience of the observer. The spectrograph is actually two completely independent units, connected only by the light rays that traverse the two components. It goes without saying that the axes of rotation of the two units must coincide exactly. They have been brought into coincidence with the aid of careful theodolite observations.

Figure 1 is a general view of the entire spectrograph. It shows the grating-lens unit at the left, the spectrograph head to the right. The various parts of the spectrograph are shown in generally correct relationships, but the perspective and relative orientation are purposely distorted to exhibit portions that would be hidden otherwise.

THE GRATING AND LENS MOUNTING

The two photographs, Figs. 2a and 2b, show the two sides of the grating and lens mounting. The grating is carried on three leveling screws in the grating box *C* (the same parts are given the same letters in all of the figures), and the lens *D* is mounted on the end of the draw tube *G* that slides in the cylinder *E*. The worm and nut, *M*, *L*, provide a focusing motion for the lens by way of the slipring *H*. The focusing motion is carried from the observer's station at the front of the spectrograph head to the worm by the rod *J*. The rod *I* transmits rotation from the spectrograph head to the worm *K*, and worm-wheel *F*, attached to the cylinder *E*. Both *E*, the cylinder in which the lens slides as it is focused, and the smaller hollow shaft at *A*, are carried on the inner races of large ball-bearings.

Electrical connections for the circuits controlling the tilt of the grating and the drift of the spectrum (motion in the direction of dispersion) are carried to the motors *O* and *B*, through the hollow shaft *A*. The grating is installed in the box *C* with its rulings parallel to the axis of rotation of the sectored gear, Fig. 2a. Rotation of the Selsyn motor *B* changes the wave-length returned by the grating through the lens to the spectrograph head. A Selsyn generator, operated by the crank, *AA* Fig. 3b, for the motor *B*, is located at the observer's station, where, by means of suitable gearing, a Veeder counter *BB* indicates the wave-length centered on the second slit or the photographic plate. It should be noted that all of the gears in the train from the Selsyn to the grating (Fig. 2a) are split and spring loaded to minimize lost motion. Tilting of the grating, which moves the spectrum perpendicular to its dispersion, is produced by the motor *O* turning the cam *N* in opposition to spring *P*. Push-buttons controlling the tilt motion are located in the observer's control box. The electrical grating controls have been very

satisfactory in use. All electrical circuits in the grating-lens unit are dead during actual observation to avoid temperature changes, and because the slight vibrations caused by sixty-cycle hum are ruinous to definition.

THE SPECTROGRAPH HEAD

The foundation of the spectrograph head is a disk of twice-annealed mild steel, five-eighths of an inch thick and forty-two inches in diameter. Two ball-bearings at *Y*, Fig. 3b, carry the weight of the plate and make rotation easy. The head is rotated by hand to the desired position and the three clamps *X* are set to prevent additional rotation. The position angle of the head is read to the nearest tenth of a degree with the aid of the vernier at *Z*. If it is desired that the spectrum fall on the second slit *S*, the grating is rotated until the dials *I* read the same as the position angle of the head. In order that the spectrum fall on the plateholder *Q* in the correct position to be photographed, it is only necessary that the position angle of the head differ from the grating rotation reading by 180 degrees. As mentioned above, this condition can be established either by rotating the grating or the head.

THE SLITS AND SLIT MOTIONS

Descriptions of the functioning and purpose of a pair of slits like those at *CC* and *S* Fig. 3b, in the usual form of spectroheliograph have been frequent and will not be repeated here. References under 3 in the bibliography are complete accounts of some of the historically important steps in the development of spectroheliographs. It will suffice to say that the spectroheliograph builds up a monochromatic picture of a plane area as large as eight by ten inches, using line elements formed by the light that emerges from the second slit. The spectral purity of the light coming out of the second slit is controlled, as in the ordinary spectrograph, by varying the width of the first slit. Variation of the width of the second slit changes the width of the line element, both geometrically and in terms of wave-length, the sharpness of the "cut-off" in wave-length depending on the first slit width. To form the monochromatic area that is the picture produced by the ordinary spectroheliograph, the line element must be moved perpendicular to its length. The McGregor spectrograph employs a small rectangle as its element of area, hence its slits must be moved so that each point on them sweeps through all points of the area to be examined. The scanned area in the McGregor instrument is 19 by 26 millimeters. Referring to Fig. 3b, the slits are swept back and forth horizontally by the cam *DD* and linkage *GG*. There is a short dwell at either end of the motion, during which the step-cam, *HH* Fig. 3b, is advanced one position by the solenoid and ratchet, *U* and *T* Fig. 3a. Changing the position of cam *HH* changes the vertical separation of the slits so that the continuous horizontal scanning motion, combined with the intermittent vertical motion provided by cam *HH*, produces the desired scanning of a rectangular area by a small rectangle. The unit area (19 by 26 millimeters) is completely scanned at the completion of each nineteenth horizontal scan. Motor *W* provides the power for the horizontal scanning. A contactor *EE* on shaft *FF* energizes the solenoid for the vertical displacement at the end of each horizontal motion. The time required for a single horizontal scan can be varied from thirty to one-half seconds. A tachometer *V* indicates the rate of rotation of the variable speed motor *W*.

The normal dimensions for both slits, when the scanning motion is used, are one-tenth-millimeter width and one-millimeter length. A lens is placed close behind the second slit to image the grating of the spectrograph on a photoelectric cell. In this way a stationary spot of light is obtained on the photoelectric surface as the slits carry out their motion. If, now, an image of the sun is projected on the first slit, diaphragmed to its normal dimensions of one-tenth-millimeter width and one-millimeter length, whatever variations in light intensity occur in the area scanned will travel via grating and lens through the second slit, finally reaching the photoelectric cell. After suitable amplification, the photoelectric current can be recorded on the usual photographic tape recorder. The current is a direct measure of the light intensity at a selected point in the image of the sun in a definite wave-length band.

THE PHOTOGRAPHIC PLATE-HOLDER

For those occasions when observations of the spectrum of the sun, or some of its features, are

desirable, provision has been made for direct spectrum photography. A plate-holder for two-by-eighteen-inch photographic plates is built in to the spectrograph head at *Q*, Figs. 3a and 3b. The plate-holder can be tilted about an axis perpendicular to the direction of its greatest length from minus twenty-five degrees (violet end of plate nearest the lens) to plus ten degrees (red end of plate nearest the lens). The distance of the lens from the center of the plate can be adjusted for any wave-length by means of the handle and dial at *J*, Fig. 3b, and one additional point on the plate can be brought into exact focus by tilting the plate-holder; but the spectrum will, in general, be noticeably out of focus at other points. The precision of focus throughout the 1000A length of spectrum that can be photographed on an eighteen-inch plate has been maintained by bending the plates to fit an experimentally determined focal surface. The combination of tilting and bending makes it possible to fit the plate to the focal surface with deviations less than the mean square error of a single determination of the focal length for a given spectral region. Plate bending templates have been experimentally determined and constructed for central wave-lengths at 500A intervals from a central wave-length of 4000A to a central wave-length of 6500A. An electrically operated shutter, *R* Fig. 3a, has been invaluable in controlling exposures that are often less than half a second's duration.

This description of the McGregor spectrograph must be concluded with mere reference to contemplated or only partially completed auxiliary apparatus. A Fabry-Perot interferometer, a vacuum arc source of spectra, a prism monochromator to be used before the first slit, means for standardizing spectrum photographs, and two optical methods of measuring magnetic fields on the sun remain to be completed. A full report by Dr. McMath in collaboration with members of the staff will be prepared as soon as conditions permit.

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An Optical Sighting Gauge for the Garand Rifle*

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THE American soldier is traditionally an excellent marksman. Part of the foundation of this tradition is due to the everyday familiarity of the average American male with firearms, and a great part is due to the excellent quality of our military rifles.

Regardless, however, of the ability of the marksman or the quality of the rifle, no person can shoot accurately unless he is sure of the correct position at which to set his sight with respect to the distance between himself and his target. In other words, at a distance of 100 yards a particular sight setting is necessary for accurate shooting. At any other distance a different sight setting is necessary. Also, the sight must be set laterally in order to compensate for the drift of the bullet caused by cross winds. The latter adjustment is referred to as "windage." The adjustment for various distances is called "elevation."

Military firearms use ammunition which is standardized. Within close limits, therefore, all bullets leave the rifle with the same velocity and follow the same trajectory. Based upon this trajectory, it is possible to compute the elevation and windage calibrations for the rifles. The rear sight of the Garand rifle is calibrated in this manner.

It then remains to set one point of the calibration correctly with respect to the index on the rifle. When one point is indexed, all others will be correct. This operation is known as "zero-ing," or "sighting-in" a rifle, and it is for this operation that the optical rifle sighting gauge was developed. The zero windage and the 100-yard elevation are the values which are indexed.

When rifles are manufactured in small quantities, the sighting operation is done by the trial and error method of actually firing the rifles on an indoor 100-yard range. This involves the expenditure of thousands of dollars for the construction of the range; the services of two operators—one to fire the rifles, and one to attend to the targets 100 yards away; and the firing of many rounds of ammunition. Although this method is unimpeachably accurate, it is slow and expensive. For instance, two men on one range can sight only 60 or 70 rifles in 8 hours, using from 8 to 13 rounds of ammunition per rifle.

When rifles are manufactured in quantities such as are involved in our present military production, the expense, as well as the necessarily increased equipment and time, of the above method of sighting prohibits its use. Many indoor ranges, dozens of men, and thousands of rounds of ammunition would be necessary. Some faster, less expensive method is needed.

The authorities of Springfield Armory, looking ahead to their problems, realized this need and came to the General Electric Company with the problem and with the idea that optics probably offered a solution to it. Accordingly, the problem was referred to the General Engineering Laboratory.

Many methods of optically or mechanically sighting rifles had been tried previously. This prior art had gained for itself the general title of "bore-sighting," because in its use the sights had been aligned with respect to the entire length of the axis of the bore of the rifle. Previous success had not been encouraging.

It is probable that if the construction of the Garand rifle were such that we could have conveniently worked upon the entire length of the bore, we would have done so in the initial phase of our development. However, we could not conveniently do this. Some other method of attack was necessary.

The idea then occurred to N. F. Barnes and K. R. Geiser that inasmuch as every rifle barrel has minor bends and twists, the last few inches of the bore probably do the major part of determining the trajectory of the bullet. If this hypothesis were true, it would mean that the sights should be aligned with respect to the last few inches of the bore, rather than with respect to the entire length of the bore.

* Paper presented at the Twenty-Eighth Annual Meeting of the Optical Society of America, Pittsburgh, Pennsylvania, October 7–9, 1943.

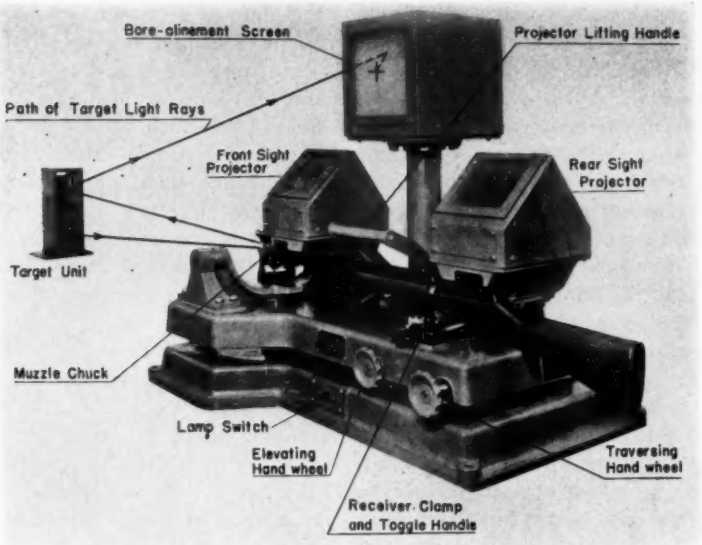

FIG. 1. Optical rifle sighting gauge, oblique front view.

Consultation with the Experimental Department of Springfield Armory strengthened our belief in the truth of this hypothesis. Mr. John Garand stated that he felt sure it was true and that we would have to determine experimentally the optimum length of bore to use. Accordingly, it was decided to conduct experiments in order to determine definitely the feasibility of the idea.

This investigation was conducted at the Springfield Armory with the cooperation of the Armory personnel, and covered a period of several months. Tests utilizing the last $\frac{1}{2}$ to 8 inches of the muzzle end of the bore for the determination of the projectile trajectory showed that the last 4 inches substantially determine the path of the bullet for a given set of firing conditions. A subsequent correlation of the data obtained indicated that it would be possible to align the sights with respect to these last 4 inches of the bore with such accuracy that, at a distance of 100 yards, approximately 82 percent of the centers of impact of a group of five shots fired from each rifle would fall within 3 inches of the center of the target. Upon the basis of these results it was decided to design and manufacture equipment incorporating the tested principle.

A further consideration of the problem made it apparent that the sighting equipment must have as its function the transferring of the sight setting of a so-called standard rifle to any other rifle. This standard rifle has been correctly sighted by firing. In order to accomplish this result the sighting gauge establishes two lines in space, one corresponding to the bore direction as determined by the standard rifle and the other corresponding to the line of sight of the standard rifle. Basically, the gauge, as shown in Fig. 1, consists of three parts:

1. A fixture for rigidly holding the rifle and accurately positioning it without placing any strain on the barrel.

2. A target optical system which indicates the alignment in space of the bore as determined by the last 4 inches.

3. Two optical projectors for producing magnified images of the front and rear sights and for indicating the sight positions relative to the rifle bore.

The muzzle of the rifle is gripped by a spring-operated 3-jaw chuck, and the rifle receiver is gripped by a clamp, the curved bottom plate of the trigger assembly being seated in a V-groove in the base of the clamp. Positioning of the rifle is accomplished by elevating and traversing the

rear of the rifle by means of two hand wheels, the left hand wheel controlling the elevation, and the right one the traverse.

When the rear of the rifle is traversed and elevated, the resulting motion takes place about a point at the center of the bore at the muzzle, this point also being the center of the chuck. The small gimbal which supports the chuck is for the purpose of preventing any strain being placed upon the barrel.

The alignment of the bore axis in space is determined by a fixed point—the bore axis at the muzzle—and two angles measured in a horizontal and vertical plane and indicated by an external target optical system. This system consists of a light source and field lens, a cross-shaped aperture, a concave mirror mounted upon the end of a 4-inch bore plug which is inserted into the muzzle end of the rifle, an adjustable plane mirror above the light source, and a mirror and ground glass screen on the main fixture.

The light bulb, lens, aperture, and adjustable mirror are mounted in a separate target unit, shown in Fig. 2, approximately 2 meters in front of the main fixture and facing it.

Light leaves the lamp bulb, goes through the lens and aperture, and falls upon the concave mirror which is mounted upon the end of the bore plug, with its axis coincident with that of the plug, as shown in Fig. 3. From the concave mirror the light is reflected to the adjustable plane mirror mounted above the light source, and then back again toward the main fixture to the mirror which throws the cross image upon the viewing screen. The concave mirror has a focal length such that it focuses an image of the cross aperture upon the viewing screen. A cross is marked upon this screen to indicate where the reflected cross should fall, the two crosses being superimposed when the rifle is correctly positioned.

FIG. 2. Target unit for optical rifle sighting gauge.

The sight projectors are optical systems designed to produce magnified images of the sights upon the viewing screens. The resulting magnification is about 25 times. The correct positions of the sights relative to the bore axis for correct firing at a 100-yard range are indicated by outlined sight image positions on the viewing screens. Also shown on these screens are "one-click" variations, each so-called "click" representing a variation in position of either sight in elevation or windage necessary to move the center of impact on the target 1 inch at 100 yards.

The projectors are mounted on separate arms so that they may be moved up to permit the insertion and removal of the rifle. The two arms rotate about a common shaft, and are raised by a handle attached to the shaft. The arms and projectors are held in the up position by an automatic latch. Each projector arm has a dash pot which gently lowers the projector over the sight, thereby preventing jarring when the projectors are dropped. Individual stops determine the downward positions.

The sighting equipment is first adjusted to a standard rifle. This rifle is one which has been selected by actual targeting on the basis of correct grouping and shooting at 100 yards' range with the sights set at their theoretically correct positions. This standard is clamped in the fixture, the sight projectors lowered, and the bore plug inserted into the muzzle end of the bore.

With the elevation and traversing motions of the fixture centered, the sight projector optics are so adjusted that the two sight images fall upon their respective outlined positions. Finally the plane mirror on the target unit is adjusted so that the image of the cross aperture, as

formed by the concave mirror on the bore plug, is superimposed upon the marked cross on the middle viewing screen.

After these adjustments have been made, the sighting equipment is ready for the production alignment of rifle sights. In order to carry out such an alignment, a rifle is clamped into position in the sighting gauge, and the bore plug carrying the concave mirror is inserted into the muzzle end of the bore. The elevation and the traverse of the fixture are then adjusted so that the cross image on the center viewing screen is superimposed upon the marked cross on that screen. The rifle is then in the correct position to fire at the same target point as the standard rifle with which the gauge was adjusted. The projectors are then lowered into position so that the magnified sight images appear upon the viewing screens, thereby showing the sight locations relative to those positions required for correct alignment. The sights are then moved to their correct positions and indexed.

These sighting operations, which require a space of less than one-twentieth of that required by a 100-yard range, can be performed at a rate of about 40 per hour. Correlation of the sighting gauge data with actual firing data shows that approximately 85 percent of the centers of impact of a group of five shots fired from each rifle fall within 3 inches of the target center at a distance of 100 yards. Rifle variations within manufacturing tolerances account for deviations between optical sighting alignment and that obtained from firing. Those manufacturing variations which would cause a marked difference between the center of impact and the target sighting point cannot all be detected by the optical sighting gauge since the operation of the latter assumes that mechanically perfect rifles are used.

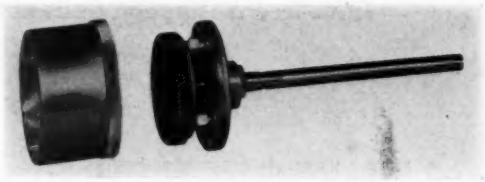

FIG. 3. Bore plug and mirror assembly. Cover removed to show adjustment screws.

It is hoped that the principles embodied in this equipment will be applicable to the "sighting-in" of other armament including that for aircraft so that the saving of time, equipment, and money through the use of the sighting gauge for the Garand rifle can be extended to the rest of the armament industry.

Infra-Red Absorption Cells and Measurement of Cell Thickness

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(Received November 2, 1943)

INFRA-RED ABSORPTION CELLS

IN a study of methods for quantitative analysis by means of infra-red spectroscopy a convenient type of constant thickness cell and a precision variable cell for volatile liquids have been developed. The former is simple and differs sufficiently in construction from cells previously described[1] to warrant a brief description. Since no precision variable cell for use with volatile liquids has been described in the literature, as far as we are aware, and since such a cell has many important uses, the variable thickness cell will be described more fully.[2] Methods for measuring cell thickness will also be discussed.

The completed fixed thickness cells are shown in Figs. 1 and 2. Holes, drilled into polished plane rocksalt plates (2.5×4.0×0.7 cm), serve as conduits for filling and emptying the cells. Lead spacer rings are cut from freshly rolled foil of thickness ranging from 0.05 to 1.0 mm in such a manner that the holes in the rocksalt plates fall inside the rings but close enough to the inside edge of the ring to permit complete filling, draining, and flushing. For cells of 0.015- to 0.05-mm thickness the spacer ring may be 1, 2, or 3 thicknesses of the pre-war cigarette package foil amalgamated together. The surfaces of the spacer ring are coated with mercury to form an amalgam layer, the cell is clamped in its holder, and the amalgam is allowed to harden. The amalgam then forms a tight seal between the rocksalt plates and the spacer. When the amalgam has hardened the plates are held together securely enough to permit removal of the supporting frame and repolishing of the outer surfaces. Repair of the inner surfaces necessitates replacement of the spacer ring, since the ring will have a hard amalgam surface which must be removed, and since thin rings will be ruined in the process of stripping them from the plates.

For thicker cells (0.5 to 1 cm or more) the spacer ring is more conveniently made of brass.

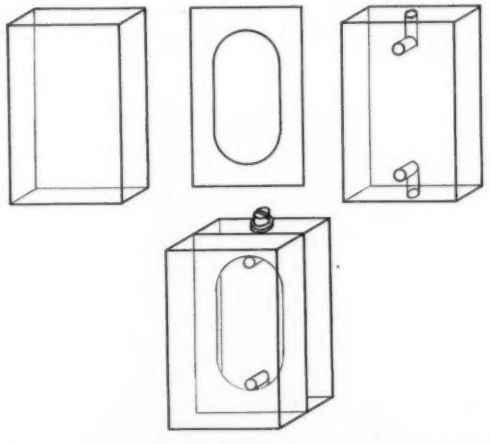

FIG. 1. A completed absorption cell with supporting frame removed and its component parts. The cell is closed by tapping the conduits drilled into the rocksalt plates and inserting a screw carrying a Neoprene washer.

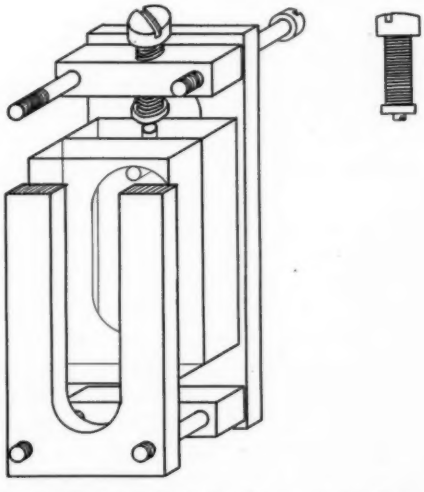

FIG. 2. Complete cell showing the supporting frame and the sliding bracket carrying the closing screw. The Neoprene washer attached to the closing screw by a small screw is pressed against the top of the cell with the head of the small screw fitting into the conduit.

* Present address: Naval Research Laboratory, Washington, D. C.

[1] L. Gildart and N. Wright, Rev. Sci. Inst. **12**, 204 (1941).

[2] A cell for non-volatile liquids has been described by E. S. Barr, Rev. Sci. Inst. **12**, 396 (1941).

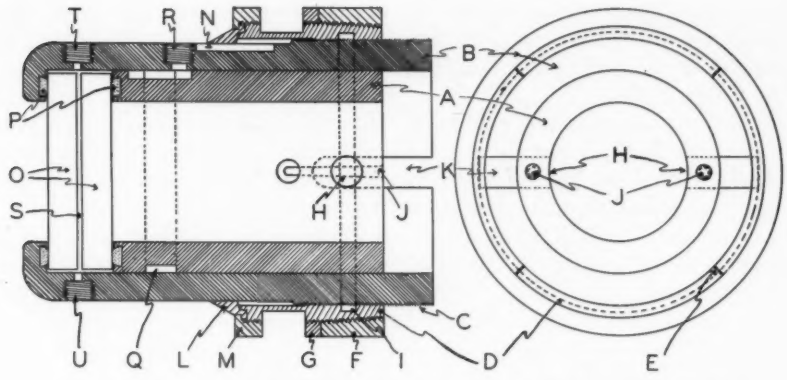

FIG. 3. Cross section of the variable absorption cell suitable for volatile liquids.

Since it is not easy to obtain an amalgam layer on brass which will harden properly, it is necessary to use thin lead gaskets between the brass and the rocksalt plates. These lead gaskets are amalgamated on both surfaces and form a tight seal as in the thin cells. In thick cells the holes for filling and emptying may be drilled into the brass spacer rather than through the rocksalt plates.

Several methods for closing the filling and draining conduits have been used, two of which are illustrated in Figs. 1 and 2. The holes in the rocksalt plates may be tapped and a small screw carrying a Neoprene washer inserted. Because of the fragility of the rocksalt the threads chip off and strip with use. Another method of closure employs a screw mounted in a sliding bracket on the holder and carrying a Neoprene washer which is pressed against the rocksalt plate.

The variable cell, shown in Fig. 3, consists essentially of two concentric cylinders carrying polished rocksalt windows between which the liquid to be studied is introduced. The separation between the windows is varied by means of a nut on the outside cylinder which is connected to the inner cylinder through slots in the outer cylinder. The separation is measured by a linear and a circular scale attached to the outer cylinder and the driving nut, respectively.

All exposed parts of cylinders *A* and *B* except the driving threads *C* are chromium plated. The outer surface of *A* and the inner surface of *B* have a thick chromium plate to permit lapping the two surfaces in order to obtain the close fit necessary. In an improved model, the entire cell is being made of stainless steel. The difference in diameters of the outer and inner surfaces of cylinders *A* and *B*, respectively, is not more than 0.0001 inch. The nut *D* working on the driving threads is chromium plated except for the threads. The driving threads *C* and those in the nut are of one-half-millimeter pitch and are lapped smooth.

The slots *E* in the nut *D* are to permit adjustment of the backlash in the driving threads, this being effected by the tapered nut *F* and lock nut *G*, both of which are chromium plated and knurled on the outer surface. The driving nut is attached to the inner cylinder through two pins *H*, the ends of which are milled to fit the groove *I* in the driving nut. These pins fit into holes in cylinder *A* and are positioned by the taper pins *J*. The slots *K* in the outer cylinder fit the pins *H* accurately to prevent rotation of cylinder *A* and provide the means of sliding cylinder *A* in *B*. The ring *L* carrying the circular scale is attached to the nut *D* by means of the nut *M*. The linear scale is placed in the groove *N* and is adjustable.

The rocksalt windows *O* are held in place by amalgamating the surfaces of the lead rings *P* which are made by pressing thin amalgamated lead rings into the grooves cut in the cylinders *A* and *B*. The amalgam between the rocksalt plates and the lead rings is allowed to harden with considerable pressure on the plates. This pressure is applied by forcing the inner cylinder

in by means of the nut *D*. This also helps to get the inner surfaces of the plates parallel. The amalgam provides both seal and mechanical support for the rocksalt plate.

Mercury is introduced into the groove *Q* through the threaded inlet *R*. A 10-cm standpipe is screwed into *R* to provide a head of mercury. The ring of mercury in the groove *Q* provides a seal to prevent the liquid introduced into the space *S* from flowing out between cylinders *A* and *B* by capillary action.

The liquid to be studied is introduced and removed through the threaded outlet *U*. A ground-glass stoppered reservoir (not shown in the figure) is screwed into *T* and a steel pipe containing a small metal stopcock is screwed into *U*. Filling of the cell from the bottom is accomplished by attaching a rubber suction bulb to the top of the reservoir. The reservoir is made of glass and attached to a threaded brass tube by a lead amalgam packing seal. The outlet and reservoir tubes are screwed against lead washers in the bottom of *T* and *U*. The steel stopcock in the outlet tube is ground with rouge and no lubricant is used. Likewise, no lubricant is used between cylinders *A* and *B*.

This cell permits the attainment of very thin films of the liquid under study as well as thick ones, up to one centimeter. The circular scale carries 250 divisions permitting the reading of the liquid film thickness to less than 0.002 mm. The ratio of volume to thickness for this cell is nearly as small as possible for a circular cell.

MEASUREMENT OF CELL THICKNESS

Multicomponent analysis and measurements of extinction coefficients necessitate an accurate determination of cell thickness in the case of fixed cells and of changes in thickness in the case of the variable cell. Several methods, adapted to the accuracy needed and the thickness of the cells, have been used for measuring the thickness of the fixed cells.

Fixed cells of 5 mm or more in thickness may be measured before assembly by means of a micrometer by measuring the thickness of the brass spacer and lead gaskets. Since the increase in thickness on amalgamation is only of the order of 0.01 mm, this method is sufficiently accurate.

Cells of thickness 0.1 to 5.0 mm are conveniently measured after assembly by use of a traveling microscope. This is done by focusing through one of the rocksalt plates on the two inner surfaces of the cell. By this method the separation of the surfaces can be measured to about 0.005 mm. At a thickness of 0.1 mm this inaccuracy becomes too large, and other methods are required.

Thin, as well as thick, cells can be measured by comparing the extinction due to concentrated solutions in the thin cells with that of dilute solutions in a thick cell which has been measured by one of the above methods. In some of the thickness measurements made by this method, the 3.4-micron band of *n*-hexane in carbon tetrachloride was used. For a two-component mixture obeying Beer's law

$$\log (I_0/I) = (\epsilon_1 c_1 + \epsilon_2 c_2) l + K, \qquad (1)$$

where I_0 is the intensity of the incident radiation and I the intensity of the transmitted radiation, ϵ_1 and ϵ_2 are the extinction coefficients of *n*-hexane and carbon tetrachloride, respectively, and c_1 and c_2 their respective concentrations. l is the thickness of the liquid layer and K represents the loss of radiation due to the rocksalt plates.

From Eq. (1) one may obtain the thickness of the cell by plotting $\log (I_0/I)$ *vs.* $(\epsilon_1 c_1 + \epsilon_2 c_2)$, the slope of the curve being l if Beer's law is obeyed. I_0 and I must be corrected for background radiation, but since K does not change with the concentration of the solution (unless there is a large change in the index of refraction of the liquid) it need not be known.[3] The precision obtainable by this method is comparable to the precision of analyses by the infra-red method and the precision of the extinction coefficients. If the precision desired is not so high, one may neglect the term $\epsilon_2 c_2$ since the absorption of carbon tetrachloride at 3.4 microns is very weak.

The extinction coefficient method has proved very useful in the calibration of the variable cell below 0.1 mm. While an optical lever connecting the inner and outer cylinders is useful for calibrating the screw and drive on the variable cell, the extinction coefficient method locates the zero point on the scale and calibrates the very thin region with much greater precision.

[3] Cf. J. Rud Nielsen and Don C. Smith, Ind. Eng. Chem., Anal. Ed. **15**, 609 (1943).

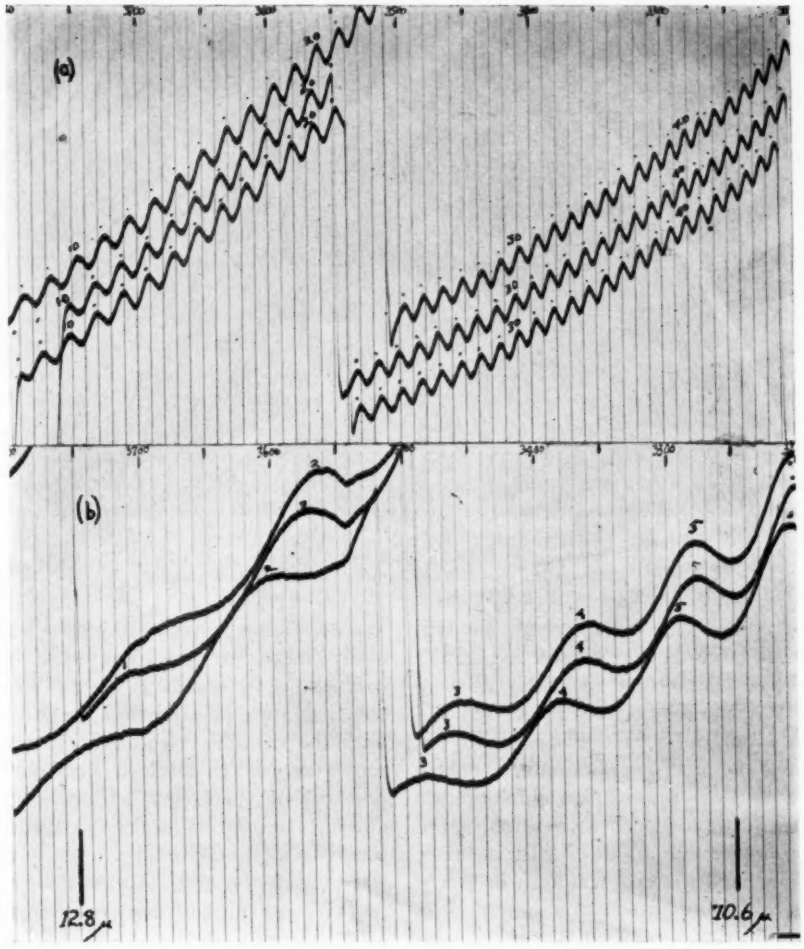

FIG. 4. Interference fringes obtained with an empty cell in the region 10.4 to 13.0 microns (a) observed with three thicknesses of the variable cell around 1.0 mm and (b) with three thicknesses around 0.15 mm.

When an empty absorption cell is placed in front of the spectrograph slit, interference fringes are often observed in the continuous spectrum if the cell thickness is below about 2 mm. Figure 4 shows such fringes in the region from 10.4 to 13.0 microns obtained with three different thicknesses of the variable thickness cell around 1.0 mm and with three thicknesses around 0.15 mm. In Fig. 5 are shown the fringes obtained in the region below 4.3 microns with six different thicknesses between 0.09 and 0.03 mm.

This phenomenon may be utilized for a precise and convenient method of determining the cell thickness. The relation between the thickness l of the cell and the number n of interference fringes between the wave-lengths λ_1 and λ_2 is

$$2l = n\lambda_1\lambda_2/(\lambda_1 - \lambda_2). \qquad (2)$$

From this relationship it is easily seen that the precision of the measurement of l depends on the precision with which $\lambda_1 - \lambda_2$ is determined. If a large wave-length range is used, it is possible to obtain an accuracy of 0.1 percent or better in l. However, since this precision is rarely needed, the wave-

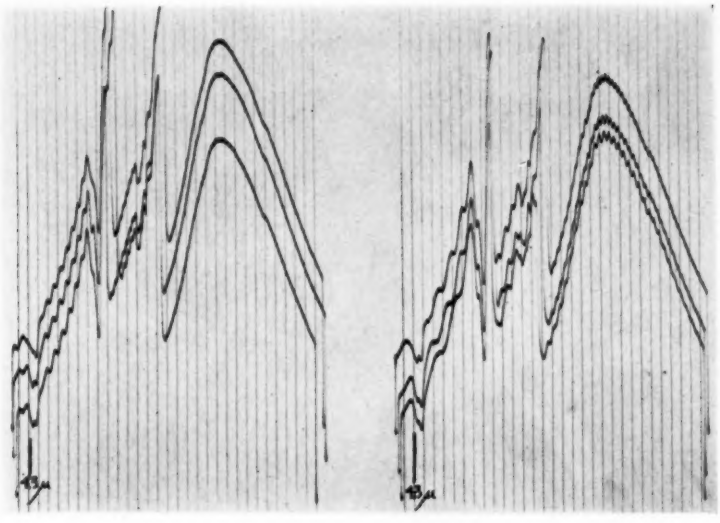

FIG. 5. Interference fringes in the region below 4.3 microns observed with six thicknesses of the variable cell between 0.09 and 0.03 mm.

length range over which the fringes are counted need not be as large as that shown in Fig. 4.

This interference method has been used to measure cell thicknesses between 0.005 mm and 2.0 mm. This method is particularly useful for thin cells, since the precision obtainable is nearly independent of the cell thickness and depends primarily on the wave-length calibration of the spectrograph. A combination of this method, which requires that the cell windows be fairly plane and parallel, and the extinction method previously outlined can be used to measure the thickness of cells which are not well enough made to give good interference fringes.

Interference fringes obtained with cells of precisely measured thickness may be used for calibrating, or checking the calibration of, the spectrograph. The interference fringes obtained with the variable cell at thicknesses below 0.15 mm were used to check and correct the calibration of the spectrograph between 2.5 and 4.0 microns, and to calibrate the spectrograph between 1.1 and 2.5 microns.

The writers wish to express their indebtedness to Professor J. Rud Nielsen who directed this work and suggested the interference method, and to Mr. Ralph Fearnow, instrument maker, who constructed the variable cell.

Fluorescence and Absorption Spectral Data for Pterin-Like Pigments Synthesized by the Diphtheria Bacillus and Isolated by Chromatographic Analysis*

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THE yellow pigment known as xanthopterin that is characteristic of the brimstone butterfly (*Gonepteryx rhamni*) has in recent years been reported to be of biologic significance. Koschara[1] has separated from human urine a pigment, uropterin, apparently identical with xanthopterin. This substance is present in mammalian tissue and, in some instances, its concentration parallels approximately that of flavin. The two pigments probably act as a functional unit in sharing with one another a role in tissue oxidation.[1] Flavin has been isolated from diphtheria toxin,[2] and recently, pterin-like pigments[3] have been found in ultrafiltrates of diphtheria toxin. This paper records the observations on these pigments.

The materials used were synthesized by a toxigenic diphtheria bacillus grown in synthetic medium[4] under conditions favorable for toxin production. They were separated from the toxic culture filtrate by ultrafiltration[5] through a Parlodion 9 percent membrane. They were then extracted with acetic acid ether (Fischer's classical method) and ultimately separated by chromatographic analysis combined with fluorescence analysis on a column of aluminium oxide standardized according to Brockmann[6] (Merck, Rahway, New Jersey), hereafter called alumina.

The acetic acid ether extraction was made from approximately ten liters of the ultrafiltrate and concentrated by evaporation at room temperature (protected from light) to a volume of about 200 ml. In the ultraviolet light from a Hanovia quartz lamp, the extract fluoresced in the depths of the solution with a deep reddish light and with an intense yellowish light on the surface.

Observations in ultraviolet light of the zones formed by washing a few drops of the extract on a thin wedge of alumina in a Petri dish revealed the presence of a number of fluorescing zones (some not visible in daylight) yielding colors other than the red fluorescence which might be attributed to porphyrins observed in our previous studies.[7] This micromethod[8] of chromatographic analysis indicated the practicability of separating the materials for spectroscopic studies on a Tswett column, that is, a chromatograph of alumina, by a combination of chromatographic and fluorescence analyses.

Different procedures were followed in the exploratory experiments of "developing" the chromatograms. In some cases the chromatograph was previously moistened with a polar solvent, as alcohol or water, in others, the investigated solution was poured on the dry, untreated adsorbent. In certain instances, the acetic acid ether solution before it was poured on the column was treated with sodium acetate until Congo red paper just turned blue. The materials washed down the column with various solutes were allowed to percolate through under gravity or with very gentle suction. The solutes used to wash the columns were first passed through a "trap," that is, another column of alumina to remove impurities which in some cases yielded a very faint fluorescence.

Since it was necessary to conserve our small supply of the ether extract for a considerable number of technical experiments, only 5-ml

* Paper presented at the Twenty-Eighth Annual Meeting of the Optical Society of America, Pittsburgh, Pennsylvania, October 7–9, 1943.

[1] W. Koschara, Zeits. f. physiol. Chem. **240**, 127–151 (1936); *ibid.*, **250**, 161–174 (1937). W. Koschara and A. Hrubesch, *ibid.*, **258**, 39–46 (1939). W. Koschara, S. von der Seipen, and P. A. Aldred, *ibid.*, **262**, 158–167 (1939). W. Koschara and H. Haug, *ibid.*, **259**, 97–112 (1939).

[2] M. O'L. Crowe, Proc. Soc. Exper. Biol. Med. **42**, 212–215 (1939).

[3] Augustus Wadsworth and M. O'L. Crowe, J. Infect. Dis. **73**, 106–123 (1943).

[4] Augustus Wadsworth and M. W. Wheeler, J. Infect. Dis. **73**, 95–105 (1943).

[5] A. B. Wadsworth, *Standard Methods of the Division of Laboratories and Research, New York State Department of Health*, second edition (Williams and Wilkins, Baltimore, 1939), pp. 531–539.

[6] Hans Brockmann and Hella Schodder, Ber. d. D. Chem. Ges. **74B**, 73–78 (1941).

[7] A. Wadsworth, M. O'L. Crowe, and L. A. Smith, Brit. J. Exper. Path. **16**, 201–217 (1935).

[8] M. O'L. Crowe, Ind. Eng. Chem., Anal. Ed. **13**, 845–846 (1941).

samples were, in most cases, used on the column. Hence, very small quantities of material were available for the determination of absorption and fluorescence spectra and for making other tests, and, therefore, the range of the ultraviolet spectra observed was restricted in scope and the visible range could not at this stage be explored.

On the chromatograph, fluorescing pigments were separated that closely resemble in certain respects those of the pterins (pigments having a purine or pyrimidin type of structure) that were isolated from the wings of butterflies and from the integument of other insects, by Schöpf and Becker,[9] and others. It has not been possible to repeat all the tests that the German workers have used in their exhaustive studies of the pterins dealing with considerable quantities of pigment extracted, in some cases, from the wings of a million butterflies.

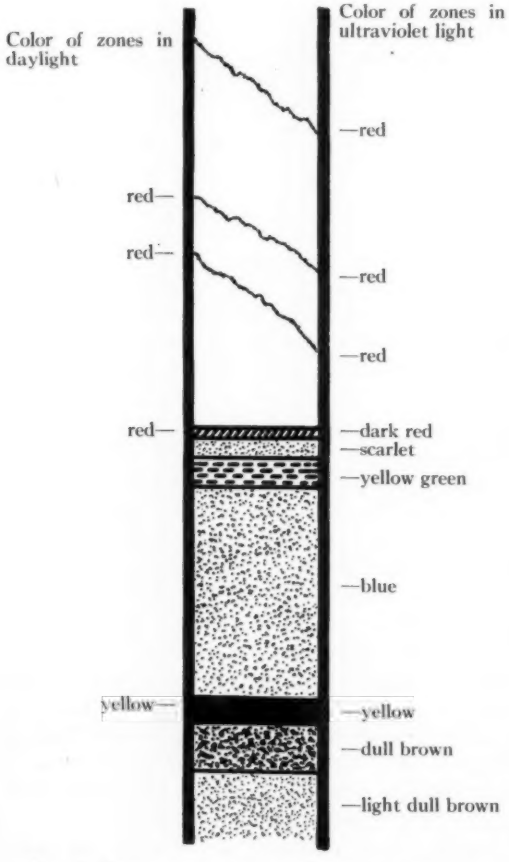

FIG. 1. Separation of the upper zones formed on a chromatograph of certain components of an ether extract from diphtheria toxin, manifested by their fluorescence in ultraviolet light.

After the acetic acid ether extract from the diphtheria toxin ultrafiltrate was poured on the column, it was washed with various solutes in the following order: anhydrous ether, methyl alcohol, distilled water, and $M/15$ borate buffer, pH 9.2.

When the column was first washed with ether a solution passed out that was yellow in daylight and fluoresced in ultraviolet light with a brilliant yellow light. Subsequent washing with methyl alcohol resulted in a more definite zoning in the column. The solution that was washed out fluoresced with a cool greenish-yellow light and was yellow in daylight. Further washing with alcohol resulted in solutions yielding only faint nondescript fluorescence. Two red fluorescing zones were left on the column; but when $M/15$ borate buffer, pH 9.2, was subsequently poured on, several narrow, brilliantly fluorescing zones of different colors appeared near the top of the column which had been previously a murky grey both in daylight and in ultraviolet light. Two of these sharp zones were visible in daylight—one dark red and below it a yellow zone.

This pattern of the fluorescing zones near the top of the column resembles the chromatographic behavior of certain of the groups of pterins described by Schöpf and Becker.[9] In their studies erythropterin is adsorbed on alumina at the top of the column in a red zone (dark red-brown in ultraviolet light); xanthopterin forms below the erythropterin a sharp yellow zone (of bright yellow fluorescence). Crysopterin forms a zone yielding a yellowish-green fluorescence just below the erythropterin and above the xanthopterin. The xanthopterin is reported to move down the column at a more rapid pace than the erythropterin when the column is washed with borate buffer. We also have observed that the yellow fluorescing zone, yellow in daylight, at the top of the column moved ahead of the sharp red fluorescing zone in one experiment about 2 cm each time 5 ml of borate buffer

[9] Clemens Schöpf and Erich Becker, Ann. d. Chemie **507**, 266–296 (1933); *ibid.*, **524**, 49–123 (1936). Erich Becker and Clemens Schöpf, *ibid.*, **524**, 124–144 (1936).

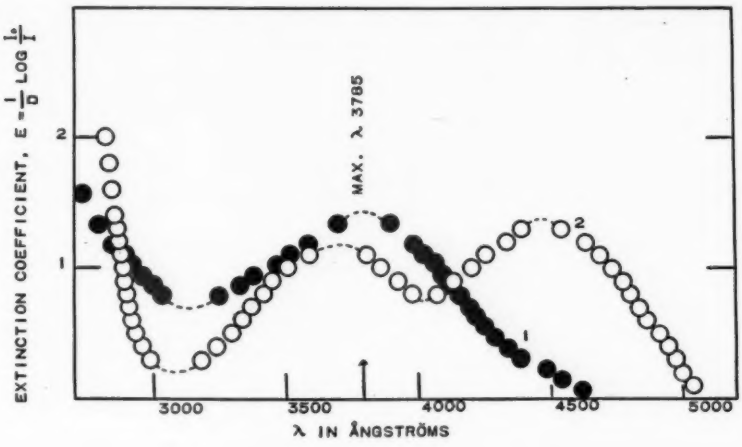

FIG. 2. Ultraviolet absorption spectrum curves.
1. Yellow fluorescing solution *B* (4.16.42) separated from diphtheria toxin.
2. Riboflavin (Merck) in *M*/15 borate buffer, *p*H 9.2.

were washed through the column. Continued washing with a relatively large quantity, approximately 50 ml, of the buffer solution resulted in the spreading and washing out of the column of the various zones in the following order: brown, yellow, blue, green, and red, shown diagrammatically in Fig. 1.

While the observations of the general chromatographic behavior and pattern of the various fluorescing zones yielded by the ether extract have proved to be useful in pointing out their resemblance in this respect to pterins, a new group of pigments not heretofore reported in the diphtheria toxin, the number of pigments revealed, and the reported difficulty of the separation of the different pterins[9] preclude an exhaustive study of all at this time. Our observations have been focused mainly on the yellow fluorescing material at the top of the column. Other yellow fluorescing zones have been observed on our columns. Flavin may constitute one of them since, in a previous study,[2] flavin was isolated from a diphtheria toxin ultrafiltrate by chloroform extraction (after an ether extraction was made to remove porphyrin and other ether-soluble material) and by subsequent chromatographic analysis. The identification of the materials in the various zones will require further studies of their ultraviolet absorption and fluorescence spectra and of other observations, such as changes which take place in color and fluorescence with changes in *p*H values, of oxidation and reduction, of crystalline forms, melting points, and other reactions.

The following experimental observations are presented as evidence that pterin-like pigments are present in ultrafiltrates of diphtheria toxin. The yellow fluorescing material that was washed from the top of the column has some characteristics that are very similar to those reported for xanthopterin.

(a) The ultraviolet absorption curve No. 1 in Fig. 2 for the yellow fluorescing solution *B* in borate buffer, *p*H 9.2, which covers a very limited spectral range, has a band maximum and minimum near the positions for xanthopterin from the wings of butterflies[9] and for uropterin[1] (apparently identical with xanthopterin). It does not resemble curve No. 2 for riboflavin in the same solvent.

(b) The fluorescence characteristics both in solution (a cool yellow) and when adsorbed on the column of alumina (a yellow green) are similar to those described for xanthopterin. A fluorescence spectrogram and the microphotometric tracing (Fig. 3) for the yellow fluorescing material in aqueous solution indicate two fluorescence bands between the helium lines λ4471 and 5876A, with maxima in the neighborhood of λ4635 and 5319A, whereas a tracing for a fluorescence

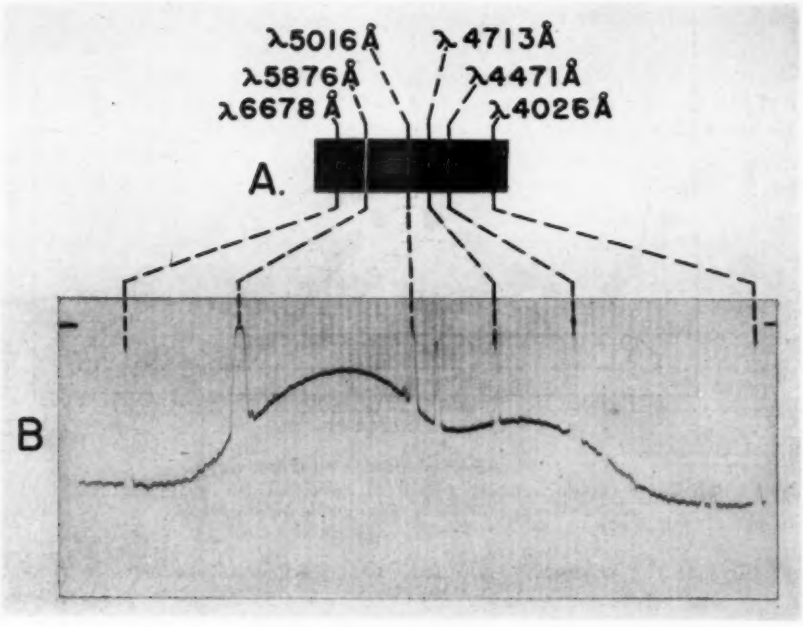

FIG. 3.
A. Fluorescence spectrogram of water solution of material No. 17 (6.7.43) separated from diphtheria toxin.
B. Microphotometric tracing of *A*.

FIG. 4. Photomicrograph of curled dried film from a solution washed from the chromatograph (×25).

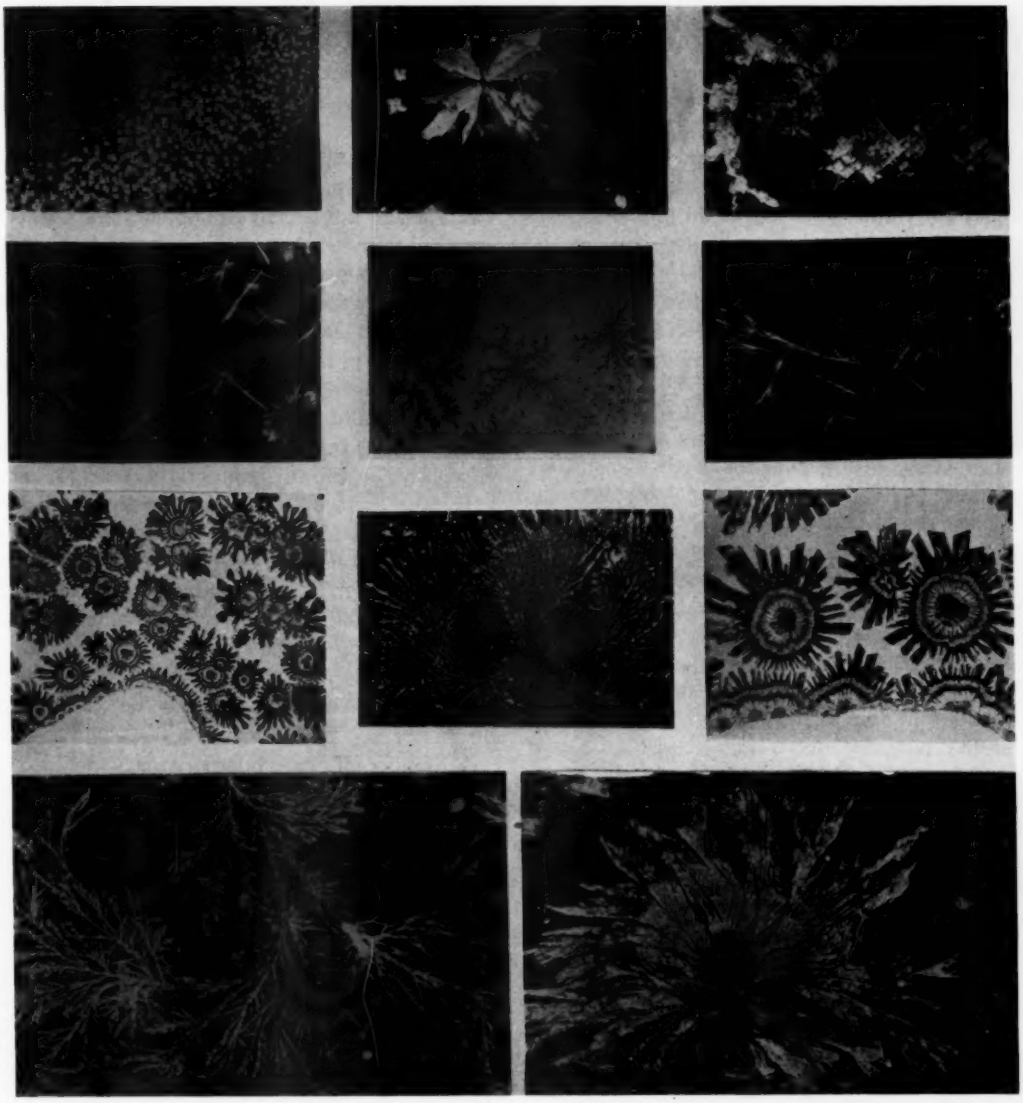

FIG. 5. Photomicrographs of the different crystal forms or aggregates of crystals from solutions washed from the chromatograph. Some were made with crossed polaroid in the light beam (×20 — ×60).

spectrogram for riboflavin (Merck) in aqueous solution shows only one band in this region with a maximum near λ5298A.

Moreover, when a small portion of the yellow fluorescing solution from the column was treated with strong sulfuric acid, its yellow fluorescence disappeared and there was indication of a very faint red fluorescence. This agrees with the report of Koschara who treated uropterin in the same manner, and also with the results of experiments by Becker and Schöpf in similarly treating a yellow solution of xanthopterin.

Treatment with hot baryta water of the yellow fluorescing solutions yielded a dense whitish

precipitate which settled to the bottom of the tube. From the yellow supernatant solution fine needles or sheaf-like bundles of crystals were crystallized out. This, according to Becker and Schöpf, excludes the possibility that the material is a flavin since a hot baryta-water solution of flavin gives a passing brownish tint but no precipitate, and salt crystals do not form from the filtered flavin solution. Similar experiments were used by Becker and Schöpf as criteria for the distinction between xanthopterin and flavin which might under some circumstances be confused when adsorbed on a chromatograph.

(*c*) Becker and Schöpf refer to a small dull brown zone on the column and to a blue fluorescing zone of "decomposition products under which is the yellow zone of xanthopterin." By reference to Fig. 1 it is evident that zones similar to these have been observed on our columns. This pattern of zones has been repeated upon several columns in different experiments.

(*d*) The crystalline structure of some of the yellow fluorescing material recovered from the column is similar to that reported for xanthopterin[9] and for uropterin.[1] As in xanthopterin "round wart-like aggregates on a membranous film-like material" have been observed for material from the diphtheria toxin. As the membranous background for some of our material dries more completely, we have observed that it breaks up into a mosaic of beautifully formed aggregates of crystals. Schöpf and Becker report yellow, wart-like crystals and remark that detailed observation of an orange-brown membrane of the pigment of crystallized xanthopterin reveals that the membrane is in reality a "mosaic of crystals joined to one another." Koschara describes the crystallization of an amorphous pigment (uropterin) in the form of "red yellow warts which moreover on long standing are accompanied by a greenish crystal membrane" or film. We also have observed in certain cases the formation of a film which did not show the mosaic effect on standing and drying but curled up and separated from the glass surface in thin irregular sheets (see Fig. 4). In some instances a greenish-blue crystal film of metallic luster was formed.

The results of these experiments indicate the separation on the chromatograph of a blue and a brown, and several yellow, green, and red fluorescing materials, some of which may be decomposition products of the others. One group of zones resembles in certain characteristics, as chromatographic behavior, fluorescent characteristics, spectral absorption, and crystalline form, the group of pterins extracted from the wings of butterflies separated on a similar chromatograph by German workers.

A number of photomicrographs which show the different crystal forms or aggregates of crystals from solutions washed from the chromatograph, for some of which we have as yet no spectroscopic data, are shown in Fig. 5.

An Application of the Spectrograph to the Inspection of Fabricated Iron and Steel*

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International Harvester Company Farmall Works, Rock Island, Illinois

THIS paper will describe the spectrographic equipment in use at Farmall Works of the International Harvester Company and discuss the operating technique and results obtained, with particular attention to the various controllable conditions which affect accuracy of results. This is not a research paper, but rather an attempt to pass on to others the details of a spectrographic installation that has been singularly successful and trouble-free, and to discuss certain interesting relations between accuracy and operating conditions which we have observed.

A spectrograph was installed in the Farmall Metallurgical Laboratory to handle the large volume of ordnance work which swelled the demand for steel and iron analysis beyond the capacity of the existing facilities. It was hoped when the installation was made that the machine would take over the analysis of all incoming steel forgings and bar stock, both plain carbon and alloy, control analysis for the plant's four grey-iron cupolas, and special jobs such as qualitative work on non-ferrous and non-metallic analysis (with the understanding, of course, that carbon, sulphur, and phosphorus would have to be run in the conventional manner). Within three weeks from the date of installation, these hopes for the most part were fulfilled, and within a month the spectrograph was the recognized analysis unit of the laboratory, operating, with few exceptions, as now will be described.

EQUIPMENT

The installation to be discussed includes an ARL Dietert grating spectrograph, high voltage spark source, densitometer, darkroom equipment, and other accessories. The spectrograph operates over a range of 2150A–4370A. The spark unit is of late design, with sealed condenser plates. The densitometer is equipped with an electronic voltage regulator and projection galvanometer. A special motor-driven cutter is used to prepare the tip of the carbon electrodes. Darkroom equipment includes a constant temperature, mechanically agitated tray holder for developing and fixing, and an infra-red film dryer. Power for the excitation unit is supplied by a $6\frac{1}{4}$ kva G.E. motor-generator set. A Westinghouse air-conditioning unit supplies humidity and temperature control.

FLAT SURFACE TECHNIQUE

At the time the Farmall Works spectrograph was installed, the conventional ferrous sample for spectroanalysis was a rod or pin turned from the sample or cast, used in pairs as electrodes. The Aluminum Company of America had for some time successfully analyzed non-ferrous materials by a spectrographic method which employed a flat surface on the sample for the upper electrode.[1] F. G. Barker of the Admiralty Laboratory, Sheffield, England, used a similar method for ferrous materials.[2] C. L. Guettel of the Rock Island Arsenal had for more than two years applied this technique to the analysis of steel. This successful operation proved to us that the spectrograph was a practical production tool, and our installation was built around the use of this sampling technique, with the addition of an

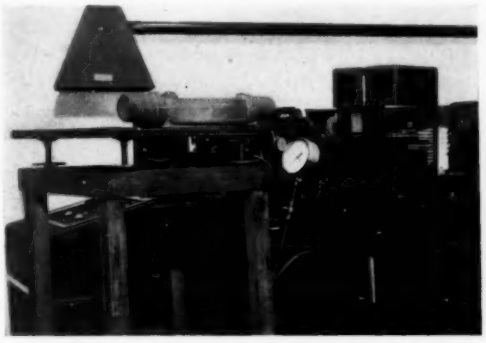

FIG. 1. Forging stand.

* Paper presented at the Twenty-Eighth Annual Meeting of the Optical Society of America, Pittsburgh, Pennsylvania, October 7–9, 1943.

[1] H. V. Churchill and J. R. Churchill, J. Opt. Soc. Am. **31**, 611 (1941).
[2] F. G. Barker, J. Iron and Steel Inst. No. I, p. 228 (1939).

TABLE I. Conditions of excitation and developing.

1. Light source	High voltage a.c. spark
2. Upper electrode	Steel sample
3. Lower electrode	Graphite
4. Lower electrode tip	Spherical end ($\frac{1}{16}$" radius)
5. Gap spacing	3 mm
6. Secondary capacity	0.007 microfarad
7. Inductance	0.182 millihenry
8. Power	$\frac{3}{4}$ kva
9. Pre-spark	40 sec.
10. Exposure	Steel—10 sec. Cast iron—15 sec.
11. Slit width	62 microns
12. Air blast pressure	0.5 pound on gauge
13. Film	Eastman's spectrum, anal. No. 1
14. Developer	D-19 (3 minutes)
15. Rinse bath	Acetic acid sol.
16. Fixer	Eastman x-ray fixer
17. Dryer	Infra-red lamp (1 min. 10 sec.)

adjustable-top table used to support large or odd-shaped specimens on the Petrey stand (Fig. 1).

For grey-iron cupola control, cast pencil-type specimens were tried, but the flat surface method was soon adopted and has proven more consistent.

The flat surface sparking technique allows analysis of rough or finished parts, where carbon, sulphur, or phosphorus is not required, without drilling or mutilating the sample, since only the flat spot is required. Being non-destructive and very rapid, it is in our opinion the key to the use of the spectrograph as a practical inspection tool.

OPERATION

Castings, forgings, samples cut from bar stock, test specimens, or parts in any stage of manufacture are brought to the spectrographic laboratory for analysis. When determination of carbon, sulphur, or phosphorus is necessary, drillings are taken and conventional analysis run. A flat spot at least three-eighths inch in diameter is then ground on the surface, and the sample is ready for the spectrograph. Conditions under which the spectrum is photographed and the film developed are shown in Table I.

The spectrograms are examined in the projection-densitometer to classify the sample as to chemical composition. Quantitative determinations of the desired elements then are made in the conventional manner except for the use of the single internal standard line. With this technique, density of the iron lines (3205A in the case of steel, or 2880A in the case of grey iron) and densities of the element lines listed in Table II are taken. From these readings, percentages are calculated. The use of this single reference method shortens the work of reading and calculating by about 40 percent. In the case of grey iron, in order to get sufficient exposure time for accuracy, we found it necessary to reduce the intensity of the silicon, manganese, and iron lines used by means of a microscope cover glass as a filter over that portion of the film. This permits use of the same excitation conditions as for steel, in spite of the much higher silicon content.

Rapid conversion of these line densities to percentage is made by means of a calculating slide-rule, composed of projections of the gamma-curve and of working curves of intensity ratio *vs.* concentration. Use of this slide-rule eliminates handling of the large calculating board, which is used only to construct the curves from which the slide-rule is prepared.

THE SAMPLE

Investigations were carried out to determine the requirements for a suitable spectrographic sample. As previously stated, a flat, ground surface at least three-eighths of an inch in diameter is required. No effect of the size of the sample was found in the tests which were run. A three

TABLE II. Element and internal standard lines.

Element line	Internal standard	Material	Concentration ranges (%)
Mn 3474.133	Fe 3205.4	Steel	0.35–2.00
Cr 2971.906	Fe 3205.4	Steel	0.20–1.80
Ni 3050.819	Fe 3205.4	Steel	0.20–3.75
Mo 3170.347	Fe 3205.4	Steel	0.10–1.00
Si 2881.578	Fe 3205.4	Steel	0.10–0.60
Al 3082.155	Fe 3205.4	Steel	0.40–1.40
Cu 3273.962	Fe 3205.4	Steel	0.05–0.20
V 3110.706	Fe 3205.4	Steel	0.04–0.25
Mn 2933.063	Fe 2880.827	Cast iron	0.30–1.00
Si 2881.578	Fe 2880.827	Cast iron	1.00–2.50

Wave-lengths as given in M.I.T. wave-length tables.

TABLE III. Effect of size of sample.

Test No.	Sample	Si	Mn	Cr	Ni	Mo
1.	$\frac{1}{16}$"×$3\frac{3}{4}$" r.d.	0.42	1.12	0.25	0.30	0.11
	$\frac{1}{8}$"×$3\frac{3}{4}$" r.d.	.42	1.12	.27	.31	.115
	$\frac{1}{4}$"×$3\frac{3}{4}$" r.d.	.43	1.14	.26	.31	.11
	20"×$3\frac{3}{4}$" r.d.	.43	1.12	.26	.31	.11
2.	Large forging	0.21	0.84			
	Small sample	.21	.85			

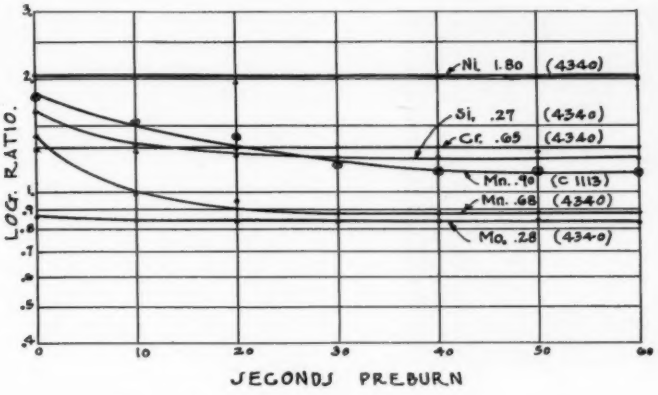

FIG. 2. Effect of preburn. A4340 and C1113 steel.

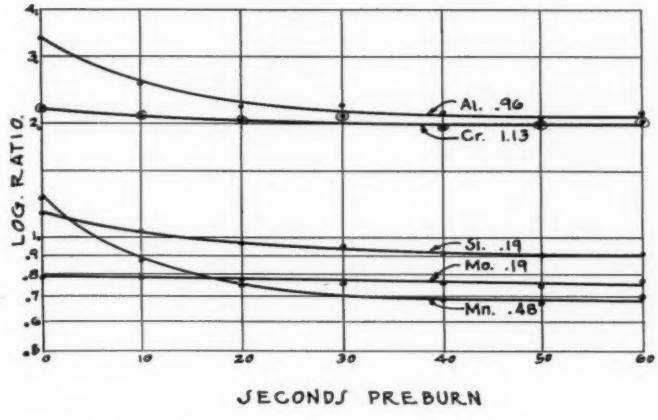

FIG. 3. Effect of preburn on Nitralloy G steel.

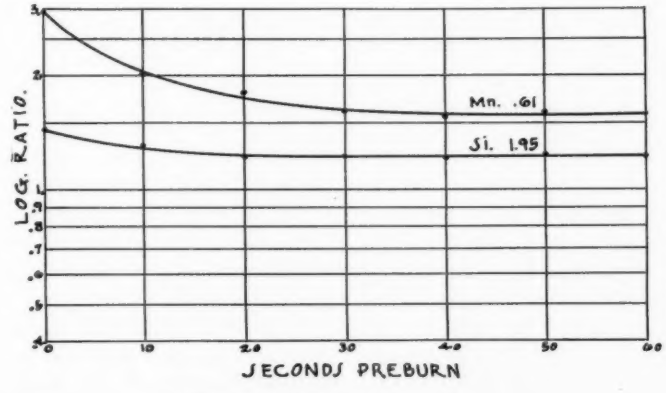

FIG. 4. Effect of preburn—cast iron.

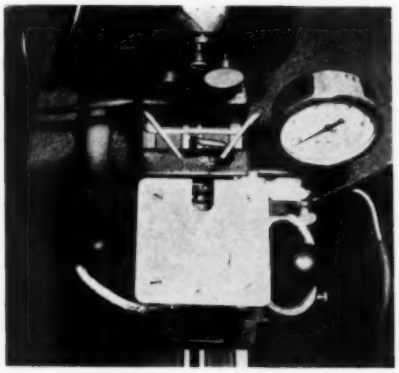

FIG. 5. Air blast.

and three-quarter-inch alloy steel bar was cut in various lengths from one-sixteenth to twenty inches, and spectrographic analysis was made of each piece. As a second test, a one-inch cube was cut from a fifty-pound forging, and a check was made on both the small and large sample. No effect of size was observed. The results are shown in Table III.

Large variations in the finish of the ground surface affect the spark, coarsely ground surfaces resulting in over-exposure of the film. It is best to standardize on a method of grinding to reproduce nearly the same finish on all samples. We use the side of a Macklin 36–10 cut-off disk. When preparing surfaces on large or odd-shaped samples, it may be impossible to produce the standardized finish. When it is necessary to deviate extremely from the standard surface, variations in exposure may be encountered, which can be compensated for by altering exposure time. Use of this compensation to maintain normal line densities will prevent any error resulting from such finish variations.

PREBURN

Errors in the analysis of high sulphur steels led to an investigation of the effect of length of preburn. Tests were run with preburn varying from zero to sixty seconds in ten-second steps, using high sulphur steel (C1113), alloy steels (A4340 and Nitralloy G), and cast iron. Results are shown in Figs. 2–4. Nickel, chromium, and molybdenum were practically unaffected. Manganese showed a marked decrease in line intensity as preburn was lengthened, leveling off in the alloy steels after about 25 seconds, whereas in the case of the high sulphur steel constancy was not reached for 40 seconds. This explains the erratic results obtained with high sulphur steels with only 20 seconds preburn, as used previous to these tests. Silicon and aluminum behave in the same manner, leveling off after about 20 seconds.

As a result of the above tests, a preburn of 40 seconds was adopted, and the result was better reproducibility and elimination of the troubles encountered with manganese in the presence of high sulphur.

AIR BLAST

The air blast used with the Farmall set-up is shown in Fig. 5. It consists of a pair of jets so arranged that the flame is blown directly away from the slit, in an attempt to prevent possible absorption phenomena. Variations in the air blast or too much air will cause erratic results. Velocity of air at the analytical gap of this unit is approximately 2500 feet per minute.

HUMIDITY

Attempts were made to determine the effect of changes in temperature and humidity on the results of spectrographic analysis. However, the air-conditioning equipment is designed to maintain 76°F and 50 percent relative humidity, and it was not possible to maintain the extreme conditions desired. A temperature of 90°F and a relative humidity of 75 percent were reached, but lack of balance at these conditions caused wide fluctuations of humidity which prevented accurate test results.

TABLE IV. Effect of variations of atmospheric condition on analysis of 1.80% Ni, 0.68% Mn steel.

Temperature	Rel. humidity	Exposure	Nickel	Manganese
76°F	50%	Normal	1.80%	0.67%
85°F	75%	Light	2.01%	.73%
85°F	75%	Normal	1.95%	.73%

Percentages shown are averages of four tests under each condition.

Some definite facts, however, were established which proved the vital need for temperature and humidity control in the spectrographic laboratory. High humidity caused low line densities.

Increasing the exposure time to correct this tendency will not remedy the abnormally high intensity ratios which result, particularly with high element concentrations. Test results showing this effect are given in Table IV.

VOLTAGE CONTROL

Variations in the electrical characteristics of the analytical spark have a definite effect on spectrographic results. For this reason it is necessary to control the voltage and power factor of the power supplied to the excitation unit as closely as possible. In our installation excellent control is obtained by the use of a generator with capacity more than double the maximum requirements of the equipment. This generator is driven by a synchronous motor which prevents transmission of line voltage and power factor variations to the spectrographic equipment.

Use of the motor-generator eliminates a source of error in the results, and we feel it is a definite factor in obtaining good reproducibility.

REPRODUCIBILITY

Each morning standard samples of Nitralloy and 4340 steel and grey iron are run, to check the working curves. Occasionally spectrographic analysis of the standards varies from the known analysis, for reasons as yet unknown to us, and corrections are made, which consist in moving the index points on the scales of the slide rule mentioned above.

In order to check the amount of this variation, a record was kept of the spectrographic results obtained on the daily check of the standards through a typical week, as calculated from the same scale without any correction. In our opinion, this was the most satisfactory test for reproducibility, since it included results over a considerable period of time and employed only daily routine analysis. Results are summarized in Tables V–VII.

TABLE V. Reproducibility tests, A4340 steel.

Type and date of analysis	Test No.	Mo %	Ni %	Cr %	Si %	Mn %
Wet analysis	1	0.28	1.80	0.65	0.27	0.68
Spect. analysis						
8–17–43	1	.28	1.79	.65	.27	.67
	2	.30	1.82	.65	.29	.69
8–18–43	3	.29	1.83	.67	.29	.70
	4	.28	1.83	.65	.29	.69
8–19–43	5	.28	1.82	.64	.27	.68
	6	.28	1.76	.63	.27	.69
	7	.28	1.79	.65	.26	.69
	8	.28	1.82	.63	.26	.69
8–20–43	9	.28	1.75	.65	.26	.69
	10	.28	1.84	.63	.26	.66
8–21–43	11	.27	1.82	.62	.27	.67
	12	.27	1.76	.65	.27	.68
8–23–43	13	.28	1.78	.63	.26	.69
	14	.29	1.85	.65	.27	.68

TABLE VI. Reproducibility tests, Nitralloy G steel.

Type and date of analysis	Test No.	Mo %	Al %	Cr %	Si %	Mn %
Wet analysis	1	0.18	0.96	1.13	0.19	0.48
Spect. analysis						
8–17–43	1	.18	0.99	1.14	.19	.48
	2	.18	0.94	1.10	.19	.49
8–18–43	3	.17	0.94	1.12	.18	.48
	4	.17	0.97	1.11	.18	.48
8–19–43	5	.17	0.98	1.13	.19	.47
	6	.18	0.97	1.16	.19	.48
8–20–43	7	.19	0.93	1.10	.19	.48
	8	.19	1.00	1.14	.20	.50
8–21–43	9	.18	0.96	1.13	.19	.48
8–25–43	10	.19	0.95	1.14	.20	.51
	11	.19	0.94	1.13	.20	.50

TABLE VII. Reproducibility tests on grey iron.

Type of analysis	Test No.	Silicon %	Manganese %
Wet analysis	1	1.95	0.61
Spect. analysis	1	1.95	.59
	2	2.00	.59
	3	1.97	.58
	4	1.92	.62
	5	2.00	.62
	6	1.93	.61
	7	2.02	.62
	8	1.93	.59
	9	1.95	.61
	10	1.95	.62
	11	2.00	.60
Wet analysis	2	2.45	.63
Spect. analysis	1	2.42	.63
	2	2.47	.65
	3	2.42	.63
	4	2.50	.64
	5	2.40	.63
	6	2.46	.63
	7	2.40	.65

SPEED AND ECONOMY

Analysis by the method described in this paper is very rapid and inexpensive. It is possible, under ideal conditions, for one operator to determine the percentages of five elements in each of nine samples of steel in thirty minutes, providing the samples have been previously prepared. Bulky samples require more handling

time. Two operators working an eight-hour day can prepare and analyze fifty to seventy-five samples, depending on the size and shape of the sample, and also prepare film processing solutions, check working curves, and take care of adjustments or other equipment maintenance.

SUMMARY

We should like to emphasize the value to us of the flat surface sparking technique. It has definitely made possible the use of our spectrograph as a successful routine analysis unit, and we feel that anyone not employing this method should investigate its possibilities.

The spectrograph has exceeded our hopes for accuracy, and we feel that the constancy of results is due primarily to three factors of control:

1. Air conditioning, providing humidity and temperature control in the spectrograph room.
2. A constant-voltage power supply, provided by a large-capacity synchronous motor-driven generator.
3. Use of sufficient preburn.

Speed and economy in our work with the spectrograph have been greatly increased without sacrifice of accuracy by the following techniques:

1. Flat surface sparking.
2. Use of a single internal standard line.
3. Calculations by means of a special slide-rule.

It is hoped that this paper will give confidence to those contemplating spectrographic analysis, and also that it has brought out some points which may be helpful to others engaged in industrial spectrography.

ACKNOWLEDGMENTS

The Metallurgical Department of the Farmall Works of the International Harvester Company, in which this equipment is located, is under the supervision of C. O. Parish and J. D. Graham. The cooperation and assistance of these gentlemen and other members of their organization in carrying out these tests and preparing this paper are appreciated. Much of the routine described was influenced by the helpful suggestions of Dr. E. S. Hodge of H. W. Dietert Company. The assistance and helpful interest of C. L. Guettel of the Rock Island Arsenal Laboratories is acknowledged.

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Experimental Determination of the Short Wave Fundamental Color in Man's Color Sense

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1. SURVEY OF ARGUMENTS HITHERTO ADVANCED FOR VIOLET AND BLUE, RESPECTIVELY, AS A FUNDAMENTAL COLOR

ACCORDING to the hypothesis of Thomas Young,[1] three processes in the retina, by acting in relatively different proportions, produce the different color sensations. The sensation that any one of these processes would produce alone, assuming that it could occur alone, is called in the present article a *fundamental* color sensation, which is the term used by Donders.[2] This expression is thus equivalent in meaning to what Young called a "principal color," Helmholtz[3] and A. König[4] "Grundempfindung," and more recent American and English authors "basic sensation."

As fundamental sensations Young assumed red, green, and violet. The same opinion had already been expressed by C. E. Wünsch[5] in 1792. Young's reason for assuming violet as the short wave fundamental color is given[6] in the following terms: "It is certain that the perfect sensations of . . . blue are produced by mixtures . . . of green and violet and there is reason to suspect that those sensations are always compounded of the separate sensations combined; at least this supposition simplifies the theory of colours: it may, therefore, be adopted with advantage, until it may be found inconsistent with any of the phenomena."

Helmholtz favored the choice of violet for the following reasons. After having criticized the view that red, yellow, and blue were the fundamental colors, he expresses himself as follows:[7] "Etwas besser würde es gehen, wenn man die Grundfarben *Violett*, *Grün*, und *Roth* wählte. Aus Violett und Grün kann man Blau mischen, aber freilich nicht das gesättigte Blau des Spectrum, und aus Grün und Roth kann man ein mattes Gelb zusammensetzen, was sich aber ebenfalls auf den ersten Blick von dem glänzenden Gelb des Spectrum unterscheidet." In another place[8] he makes the following statement: "Es konnten beliebig jede drei Farben gewählt werden, aus denen Weiss zusammengesetzt werden kann. Young ist wohl durch die Rücksicht geleitet worden, dass die Endfarben des Spectrum eine ausgezeichnete Stellung zu beanspruchen scheinen. Würden wir diese nicht wählen, so musste eine der Grundfarben ein purpurner Farbenton sein und ihre entsprechende Kurve . . . zwei Maxima haben, eines in Roth, eines in Violett. Es wäre dies eine complicirtere aber nicht unmögliche Voraussetzung. So viel ich sehe, giebt es bisher kein anderes Mittel, eine der Grundfarben zu bestimmen, als die Untersuchung der Farbenblinden."

Hering's color-sense hypothesis, advanced in 1874 by the physiologist Ewald Hering[9] in Prague, later in Leipzig, postulates that red and green, and yellow and blue are elementary "Gegenfarben"; thus ascribing the character of a fundamental color to blue, but denying it to violet.

J. C. Maxwell[10] produced an experimental basis for Young's three-color hypothesis by showing that all the colors in the spectrum could be synthesized from three spectrally homogeneous radiations, if suitably chosen. He treated the numerical values which he arrived at in his three-color synthesis mathematically, and transformed them into a modification of Newton's geometrical color diagram. This method of determining the resultant color from a mixture

[1] Thomas Young, *A Course of Lectures on Natural Philosophy* (London, 1807), Vol. II.
[2] F. C. Donders, Brit. Med. J. **2**, 768 (1880).
[3] H. Helmholtz, *Handbuch der physiol. Optik* (Leipzig, 1867).
[4] A. König and C. Dieterici, Sitz. d. Akad. d. Wiss. Berlin, p. 805 (1886).
[5] Christian E. Wünsch, *Versuche und Beobachtungen über die Farben des Lichtes* (Leipzig, 1792), p. 6.
[6] Reference 1, p. 617.
[7] Reference 3, p. 290.
[8] Reference 3, pp. 292–293.
[9] E. Hering, Sitz. d. Akad. d. Wiss. Wien. **70**, 169 (1874), Abt. III.
[10] J. Clerk Maxwell, Trans. Roy. Soc. London **150**, 57 (1860).

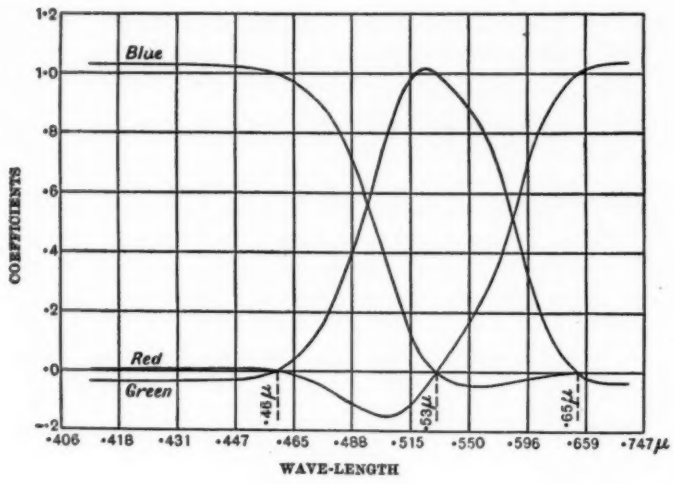

FIG. 1. W. D. Wright's coefficient curves based on trichromatic synthesis of the spectral colors by mixture of standard radiations of the wave-lengths 0.650μ, 0.530μ, and 0.460μ. Average results of 10 observers (see reference 13).

of color elements is mathematically identical with that of finding the center of gravity of two weights, and placing a weight equal to their sum at the point so found.

Maxwell seems to have held the opinion that this procedure might also provide a clue for determining the exact position in the spectrum of the three fundamental colors assumed by Young. At least he states[11] that he has strong reason to believe that the wave-lengths 2328, 1914, and 1717 in Fraunhofer units—recalculated approximately 630, 515, and 465 mμ—"are the three primary colours corresponding to the three modes of sensation in the organ of vision, on which the whole system of colours, as seen by the normal eye, depends." It is here worth noticing that the radiation of wave-length 465 mμ lies *at the very boundary between blue and indigo*, but obviously nearer to blue than to violet in Newton's sense. At all events, Maxwell, contrary to Young and Helmholtz, terms the short wave fundamental color blue.

In dealing mathematically with the values from his color synthesis, Maxwell supposes that if the retina is exposed to a spectrally homogeneous radiation, the color sensation aroused is built up exclusively of excitant impulses. At the time at which he was working (1860) there was scarcely any cause for supposing otherwise. When, however, on this assumption, he constructed from his observations curves intended to indicate the intensities of the three standard colors in different points of the spectrum, certain spectral lights turned out to arouse a negative intensity of one or other of the standard colors. He did not go into any further detail concerning this particular fact, but when he was forced to use negative values in his calculations of the center of gravity as applied to his color diagram, he stated:[12] "This, though following from mathematical principles, is not capable of direct physical interpretation, as we cannot exhibit a negative colour."

Negative ordinates in the same positions as in Maxwell's curves, but considerably more conspicuous, are likewise found in curves (cf. Fig. 1) correspondingly derived by W. D. Wright[13] from his observations on three-color synthesis.

The fact that negative ordinates can appear at all in the conditions obtaining in the experiments undertaken by Maxwell and by Wright may be attributed to the circumstance that the trichromatic synthesis must take place when the organ of vision is in a state of adaptation to light. Thus, the synthesis of a color identical with that of the beam to be analyzed must be brought about by fusion of the requisite intensities of the three standard colors, on the foundation of an already existent positive level of

[11] Reference 10, p. 74.

[12] Reference 10, p. 62.

[13] W. D. Wright, "A re-determination of the trichromatic mixture data," Special Report 139 of Med. Research Council (London, 1929).

excitation in the receptors, a level which can accordingly be subjected to reduction.

From the existence and the position of the negative ordinates in the experimental curves (cf. Fig. 1), the present writer[14] drew the conclusion that on exposing to the normal visual organ of man a spectrally homogeneous radiation which arouses a color sensation, not only is an impulse excitant of a corresponding color center released, but *at the same time, of necessity, an additional impulse is generated which produces a certain inhibition of the center for the complementary color.*

In the experiments on three-color synthesis, this assumed inhibitory process, when released by the spectrally homogeneous radiation, must, at some sections of the spectrum, produce an effect more exclusively limited to and concentrated on a wave-length region chiefly exciting *one* category of receptors than is possible when it is released by the three-color mixture, since in relation to the latter the inhibitory process must obviously be more widely distributed among the different receptor categories.

At all events, since inhibition is a suppression or depression of an excitation, and since the inhibition in this instance is assumed to affect a nervous center for the production of a color sensation *complementary to* that directly excited by the radiation, the physiological process, on assumption of an integrant inhibitory process in the synthesis of color sensations, is too complicated to be *exactly* expressed in mathematical terms. For this reason a mathematical calculation of the position of a fundamental color along Maxwell's lines cannot be expected to give a result of "mathematical certainty" from the physiological point of view. A. König and C. Dieterici, operating with Maxwell's method, somewhat modified, from their observation material concluded,[15] among other things, that the short wave fundamental color is "a blue of wave-length approximately 470 mμ." It is not easy, however, to realize how this statement can be reconciled with the fact that[16] the peak of the curve indicating the distribution of excitation of the receptors for the short wave "Grundempfindung" lies, in König's own eye, at about 450 mμ. In an article "Über Blaublindheit"[17] published later, König himself makes the following remark: "Ich will hier schon bemerken, dass ich über die Qualität dieser dritten Grundempfindung der Young-Helmholtzschen Farbentheorie —ob blau oder violett—noch kein sicheres Urteil fällen möchte. Jedenfalls aber bin ich jetzt geneigt, sie weit mehr dem Violett anzunähern, als dieses im Jahre 1886 der Fall war."

W. D. Wright refrains from making any statement concerning the position of the short wave fundamental color on the basis of his comprehensive three-color experiments summarized in Fig. 1.

Contrary to Young and Helmholtz, but on insufficient evidence, A. Fick[18] and W. Abney[19] held the opinion that blue and not violet is the short wave fundamental color. Fick alleged as reason for his opinion that the difference in hue between one fundamental color and the two remaining ones ought to be approximately equal. He remarked that the difference in hue between red and violet is obviously less than between red and green. On the other hand, the difference in hue between red and green and between green and blue is more proportionate. Abney supported his view by the following argument:[20] "If we take a patch of violet light from one spectrum and place one slit in the red near the red lithium line, and another in the blue near the blue lithium line, we can make a mixture of red and blue which will match the violet, to which a little white has been added." Earlier A. Weinhold[21] had reported, in favor of violet, that he had found it impossible to obtain a sensation equal to spectral violet by mixing spectral red and spectral blue.

The hue-discrimination curves yield no evidence which might lead to a decision between violet and blue as the fundamental color.

[14] G. F. Göthlin, Acta Ophthal. (Copenhagen) **21**, 75 (1943).

[15] A. König, Sitz. d. Akad. d. Wiss. Berlin, p. 828 (1886). A. König, and C. Dieterici, Zeits. f. Psychol. u. Physiol. d. Sinnesorg. **4**, 343 (1892).

[16] See A. König and C. Dieterici, reference 15, p. 336, Fig. 6.

[17] A. König, Sitz.-ber. d. Akad. d. Wiss. Berlin, p. 718 (1897).

[18] A. Fick, "Die Lehre, von der Lichtempfindung," *Hermenn's Handb. d. Physiol.* Vol. III: 1, pp. 209–210 (1879).

[19] W. de W. Abney, *Researches in Colour Vision* (London, 1913).

[20] W. de W. Abney, reference 19, p. 230.

[21] A. Weinhold, Ann. d. Physik u. Chem., Neue Folg. **2**, 63 (1877).

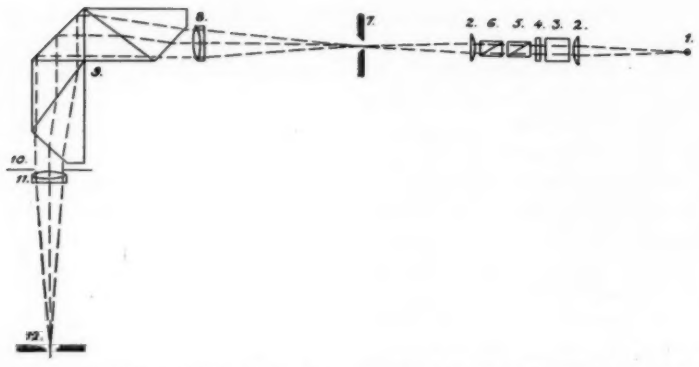

FIG. 2. Plan of Göthlin's liminospectroscope. *1.* Image of Nernst filament in a slit lamp constructed by Gullstrand. *2.* Convex lenses. *3.* Trough for heat-absorbing fluid. *4.* Holder for ray filter. *5.* Polarizing Nicol (rotatory). *6.* Analyzing Nicol (fixed). *7.* Collimator slit. *8.* Collimator lens. *9.* Constant deviation prism. *10.* Iris diaphragm. *11.* Telescope lens. *12.* Telescope slit.

The uncertainty concerning the real nature of the short wave fundamental color is evident from the fact that several scientists nowadays use the term blue and violet promiscuously when speaking of this color. Such a standpoint is, however, untenable. If one assumes that violet is the fundamental color, one binds oneself also to the assumption that the red component—which is an essential ingredient of the color sensation from the shortest wave part of the visible spectrum—is an inevitable part of the third fundamental sensation itself, and is, therefore, obviously released by the receptors for this sensation. The assumption, on the contrary, that blue is the fundamental color implies that the red component of violet is released by another receptor. In any case, most investigators have seen the problem as an *alternative* whether violet *or* blue is the third fundamental sensation. Unique is the view of G. J. Burch[22] based upon results obtained in a state of fatigue for different colors in the spectrum. As an outcome of his experiments, he concluded that *both* blue and violet are fundamental sensations.

The writer considers that the above survey shows that so far no method capable of giving clear and incontestable results concerning the position in the spectrum of the short wave fundamental color has been employed. Consequently he maintains that *up to now no decisive evidence, experimental or otherwise satisfactory, has been advanced to prove that the short wave fundamental color is violet or to prove that it is blue.*

[22] G. J. Burch, Trans. Roy. Soc. London **B191**, 1 (1899).

2. PLAN AND PROCEDURE FOR A COLOR-THRESHOLD ANALYSIS IN THE SHORT WAVE PART OF THE SPECTRUM

C. E. Wünsch, Young, and Helmholtz have unanimously assumed that the sensation of blue is normally aroused by simultaneous impulses from receptors for green and receptors for violet. Now, if the color threshold for the sensation of indigo could be split up into two, the following must, according to the assumption of the three scientists named, be expected to occur. If spectrally homogeneous energy from the intermediate spectral region of indigo is allowed to affect the eye, beginning with a sub-threshold radiant flux, and the flux is continuously increased, the first color sensation to result ought, if separation takes place, to be a sensation of one of the colors assumed to be fundamental; that is, either a sensation of violet or a sensation of green. Only with greater radiant flux, when the threshold is reached both of the receptors for green and of those for violet, would a sensation lying nearer to blue be aroused.

The aim of the experiments described in this article has been to ascertain whether this really occurs and thus to verify with what degree of justification violet can be regarded as a fundamental color without which blue could not arise.

The experiments are carried out with *the liminospectroscope*, an optical instrument manufactured to the author's design in 1915 by the firm of Schmidt & Haensch in Berlin. The construction of the instrument may be gathered from the following description and Fig. 2. The source of light is a Nernst slit lamp, constructed by Gullstrand.[23] The primary image, in the lamp slit, of the incandescent Nernst filament, gives rise to a secondary image in the collimator slit of a spectroscope by means of two semi-convex lenses of equal focal lengths. Between the two lenses is placed a polarization system, which is made up of two prisms *5*, *6* of Glan-Thompson design, and a holder *4* to which a ray filter may be attached. Such a filter is always used as a precautionary measure, in order to exclude completely any possible occurrence of stray light from spectral regions other than that under consideration. In the polarization system, the polarizing Nicol may be rotated by means of a micro-screw. The angle of rotation may be read off with a magnifying glass, to an accuracy of one minute, on a circular nonius scale. The Nicol nearest the spectroscope is fixed, and adjusted so that the plane of the electric vector—the one which causes the excitation of the retina—in the radiations passing through the spectroscope is vertical. The instrument is thus so built that the light entering and leaving the spectroscope is plane-polarized, and that its plane of vibration remains unaltered when the light is regulated by the polarization mechanism.

The collimator slit and the telescope slit are symmetrically opening slits of Wadsworth's design, with microregulators. The body of the refracting prism is made up of 5 partial prisms producing, together with the rotating mechanism, a constant deviation. The dispersion between the lines *C* and *F* amounts to 5° 30′. The extent of the field of observation can be continually varied between 45′ and 5° by means of a graduated iris diaphragm.

A characteristic of the instrument is the possibility of extremely fine regulation of the amount of light entering the eye. For a given constant width of collimator and telescope slits, adjustment may, by means of the polarizing Nicol scale, be made for $90 \times 60 = 5400$ numerically determinable amounts, without altering the wave-length composition of the light.

The amount of light passing through the instrument proved to be sufficient for color-threshold settings throughout the indigo region of the spectrum, i.e., in respect to wave-lengths between the limits 465 and 430 mμ. In certain cases rays down to wave-length 425 mμ, and in rare cases down to 420 mμ, still fall within the region in which the instrument allows a determination of the color threshold. For work with still shorter wave-lengths a quartz optical outfit would have been necessary, since the absorption in the glass material is altogether too great.

A certain absorption of light is also caused by the necessity of using a filter in order to exclude stray light completely, especially from the long wave red. For this purpose a glass filter BG12 from Jena Farbenwerke was used.

The Nernst filament in the liminospectroscope was supplied with current of 0.5 amp. from a local battery. The battery voltage remained the same during each series on the same day. Between one day and another, however, differences in the voltage level within the limits 110–115 volts were liable to occur. On comparing the results on different days one must accordingly allow for the effect of those variations on the luminosity of the incandescent Nernst filament.

For wave-length determinations within the region covered, using a collimator slit 0.05 mm and a telescope slit 0.1 mm, the Hg lines with wave-lengths 404.7 mμ and 435.8 mμ and the He line with wave-length 471.3 were chosen as fixed points to construct a curve. A wave-length formula was calculated by the method of Cornu.[24] It was checked by means of the He line with wave-length 447.2 mμ.

The analysis of the color thresholds was undertaken with radiations of wave-lengths 460, 455, 450, 445, 440, 435, and 430 mμ, respectively, and in certain cases with those of wave-length 425 mμ as well. To obtain sufficient brightness with the wave-lengths 430 and 425 mμ, the collimator slit had to be kept at a breadth of 0.5 mm and the

[23] A. Gullstrand, Ber. üb. d. 37. Versamml. d. ophthal. Gesellsch. (Heidelberg, 1911).

[24] A. Cornu, Ann. de l'École norm. [2], Part 9, 21 (1880).

TABLE I. Records of color-threshold determinations carried out with the liminospectroscope in the indigo region of the spectrum. Relative energy values are calculated for the thresholds T_1 corresponding to beginning sensation of blue, and T_2 corresponding to beginning sensation of red. The energy values are expressed in units of energy valid only for the wave-length under consideration (see text).

Experimental subject. Time	Field of observation	Wave-length in mμ	Collimator slit in mm	Observed energy value for threshold sensation of: colorless light	blue component $=T_1$	red component $=T_2$	simultaneous appearance of blue and red component	Remarks	$(T_2-T_1)/T_1$	T_1/T_2
1942										
N.G.A.	3°	420	0.5	22.7						
22. VI	3°	425	0.5	6.91			321			
22. VI	3°	430	0.5	2.24			208			
22. VI	3°	435	0.5	0.78			"blue violet" 157+/			
22. VI	3°	440	0.5	0.63	92.2	171+/		+/ Field at these thresholds violet in the central part, blue in the periphery.	0.855	0.539
22. VI	3°	445	0.5	0.36	35.3	107+/			2.03	0.33
22. VI	3°	450	0.5	0.17	26.5	60.4+/			1.279	0.439
22. VI	3°	460	0.5	0.20	35.6	++/		++/ Blue even at $E=500$.		
12. VIII	45′	425	0.5	15	343	+++/		+++/ Threshold for red component not reached at $E=500$.	2.948	0.253
12. VIII	45′	430	0.5	14.8	118	466			3.102	0.244
12. VIII	45′	435	0.5	2.94	55.1	226			2.584	0.279
12. VIII	45′	440	0.5	1.97	38.5	138			6.278	0.137
12. VIII	45′	445	0.5	0.60	16.9	123			12.855	0.072
12. VIII	45′	450	0.5	0.70	4.54	62.9			6.689	0.130
12. VIII	45′	455	0.5	0.42	4.11	31.6			123.27	0.008
12. VIII	45′	460	0.5	0.49	3.75	466				
12. VIII	45′	465	0.5		2.96	·/		·/ No red component visible at $E=500$.		
R.B.										
2. VI	3°	430	0.5		50.9	115			1.265	0.441
4. VI	3°	435	0.2		6.6	30.6			3.636	0.216
4. VI	3°	440	0.2		2.0	25.8			11.900	0.078
4. VI	3°	445	0.2		1.6	22.1			12.813	0.072
4. VI	3°	450	0.2		0.75	17.1			21.800	0.044
4. VI	3°	455	0.2		0.89	27.8			30.236	0.032
4. VI	3°	460	0.2		0.71	+/		+/ No red component at $E=200$.		
2. VIII	45′	420	0.5	15.0	++/			++/ No color at $E=500$.		
2. VIII	45′	425	0.5	6.7	+++/			+++/ At $E=500$ very faint color, probably blue-violet.	1.268	0.441
2. VIII	45′	430	0.5	2.1	157	356			1.149	0.465
2. VIII	45′	435	0.5	1.4	100.5	216			2.023	0.331
2. VIII	45′	440	0.5	0.40	52.4	158.5·/		·/ The red component fainter than in the preceding light.	2.843	0.260
2. VIII	45′	445	0.5	0.22	26.8	103				
2. VIII	45′	450	0.5	0.21	32.1··/			··/ Blue even at $E=500$.		

telescope slit at a breadth of 1.0 mm. Because of some doubt as to whether the incandescent Nernst filament is equally luminous throughout its whole breadth the same combination of slits was, in the majority of cases, used for the other wave-lengths as well.

The spectrally homogeneous light emitted from the instrument was observed by Maxwell's method, with the eye close to the telescope slit. The height of this was confined to 2.5 mm. Light leaving the instrument at the given width of the slits—0.5 mm×1.0 mm—was seen, when entering the crossed slit of another spectroscope equipped with a wave-length scale, to have the following approximate spectral breadth:

Wave-length of radiation	Spectral breadth
425–435 mμ	2 mμ
440 mμ	2.5 mμ
445–450 mμ	3 mμ
455–465 mμ	4 mμ.

The writer considered adaptation of the observers to total darkness essential in order to be quite sure that the eye was completely rested, free from after-images, and ready to undertake such an exacting task as to determine whether a

TABLE II. Records of color-threshold determinations carried out with the liminospectroscope in the indigo region of the spectrum. Relative energy values are calculated for the thresholds T_1 corresponding to beginning sensation of blue, and T_2 corresponding to beginning sensation of red. The energy values are expressed in units of energy valid only for the wave-length under consideration (see text).

Experimental subject. Time	Field of observation	Wave-length in mμ	Collimator slit in mm	Observed energy value for threshold sensation of: colorless light	blue component = T_1	red component = T_2	simultaneous appearance of blue and red component	Remarks	$(T_2-T_1)/T_1$	T_1/T_2
1942										
G.v.B.	3°	420	0.5	1.01			170			
18. V	3°	425	0.5	0.80			62.5			
27. V	3°	430	0.5	0.55			57.9			
27. V	3°	435	0.1	0.08			17.6			
20. VIII	3°	445	0.5	0.049	"bluish" 4.35	"violet" 10.94		"Bluish" = blue is perceived but an inmixture of red is not perceived.	1.515	0.398
20. VIII	3°	450	0.5	0.019	"bluish" 2.72	"violet" 24.0			7.824	0.113
20. VIII	3°	455	0.5	0.01	"bluish" 2.92	"violet" 6.47			1.216	0.451
20. VIII	3°	460	0.5	0.007			1.92			
20. VIII	3°	465	0.5	0.007	"bluish" 1.35	·/		·/Even at $E=500$ no red component.		
H.E.	3°	420	0.5		241	··/		··/Even at $E=500$ no red component.		
5. VI	3°	425	0.5		288	··/		··/Even at $E=500$ no red component.		
5. VI	3°	430	0.5		228	··/		··/Even at $E=500$ no red component.		
5. VI	3°	435	0.5		107	274			1.561	0.391
9. VI	3°	440	0.2		56.5	142			1.513	0.398
9. VI	3°	445	0.2		57.7	79.2(?)			0.373(?)	0.729(?)
9. VI	3°	450	0.2		43.8	110			1.511	0.398
9. VI	3°	455	0.2	0.024	31.0	·/		·/No red component visible at $E=200$.		
9. VI	3°	460	0.2		23.6	··/		··/No red component visible at $E=200$.		
9. IX	45′	425	0.5	40.3+/				+/Colorless even at $E=500$.		
9. IX	45′	430	0.5		184++/			++/Blue even at $E=500$.		
9. IX	45′	435	0.5	5.3	128++/			++/Blue even at $E=500$.		
9. IX	45′	440	0.5		150	488				
9. IX	45′	445	0.5		118+++/			+++/No red component visible at $E=500$.		
9. IX	45′	450	0.5		151+++/			+++/No red component visible at $E=500$.		
N.T.	45′	425	0.5	144+/				+/Colorless at $E=500$.		
26. VII	45′	430	0.5	58.3			++/	++/Color exceedingly feeble, possibly violet at $E=500$.		
26. VII	45′	435	0.5	57.4			271+++/	+++/Beginning color, probably blue violet.		
26. VII	45′	435	0.5				376·/	·/No doubt that the color is violet.		
26. VII	45′	440	0.5	14.4	225··/			··/Beginning color, hue uncertain.		
26. VII	45′	440	0.5		331···/			···/Blue even at $E=500$.		
26. VII	45′	445	0.5	11.6	330+/			+/Blue even at $E=500$.		

dissociation into two component thresholds can take place with the mixed-color sensation indigo. Accordingly, an hour's adaptation in complete darkness preceded every series of color-threshold determinations in the experiments to be described.

The main part of the liminospectroscope was lodged in one room, the observer in another. The ocular end of the telescope tube pointed through an aperture into the totally dark room occupied by the observer. The connection was entirely light-tight. When a threshold determination was to be made, the observer, by putting his hand through another padded and opaque tunnel in the same wall, could himself adjust the screw

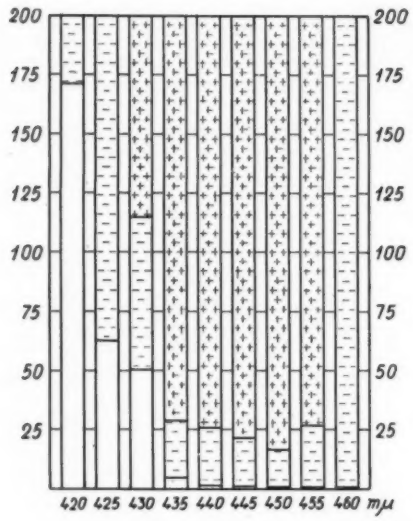

FIG. 3. Diagrammatic representation of the relative energy values of the thresholds for a blue and a red component in spectral indigo, in accordance with determinations by observer R.B.; the parts of columns which are marked with horizontal lines represent sensations of blue; the parts marked with crosses represent sensations of violet. Field 3°.

controlling the instrument's polarization mechanism. At the start this was adjusted to 0 on the scale, that is, the field of vision was totally dark. When the observer, by means of the screw, had found the threshold for light sensation he had, while fixing the field centrally, to continue this adjustment to determine the color threshold or—when there were two—color thresholds. The angle corresponding to each color threshold was observed and a record kept by the operator. The color-threshold determinations always took place when the light was continuously increasing in brightness, never during decreasing brightness. If the polarization device, starting from 0 on the scale (when complete extinction of light takes place), is turned through an angle of γ circular degrees, the radiant energy is assumed, in accordance with Malus' law, to vary in proportion to $\sin^2 \gamma$.

The investigation aimed at ascertaining the energy relationship between the thresholds of two possibly distinguishable components in a radiation of given wave-length. This was achieved in the following manner. As unit —valid only for the wave-length to which it is referred—the author has chosen 1/100 of the radiant flux which leaves the telescope slit and on correct connection penetrates in its entirety into the eye when the instrument is adjusted to the wave-length in question, the collimator slit amounting to 0.1 mm, the telescope slit to 1.0 mm in width, and the polarization planes of the Nicols being parallel.

3. DETERMINATIONS AND STATISTICAL TREATMENT

The investigation was carried out in the Physiological Institute of Upsala University. Several of my younger colleagues allowed themselves to be used there as subjects for the threshold analyses: Messrs. Nils Gunnar Ahlborg, Gunnar von Bahr, Runar Brenning, Henrik Enghoff, and Nils Törnblom. It gives me great pleasure to express here my gratitude to them for their careful fulfillment of a task which was by no means easy.

As criteria for assessing their suitability as subjects I give below particulars as to their ages, refraction, visual acuity, and green-red coefficients when tested for the Rayleigh equation with Göthlin's[25] polarization anomaloscope. On diagnostic examination they all proved to be normal trichromats.

N.G.A.: physician, 29 years of age; in left eye, the one used in the experiments, emmetropic refraction and no demonstrable astigmatism, visual acuity at least 1.0; green-red coefficient 1.063.

R.B.: M.D., lecturer in physiology, 38 years of age; in left eye, the one used in the determinations, mixed astigmatism 1.5 D., visual acuity without correction (as in the experiments) = 0.8, after correction 1.5; green-red coefficient 0.788.

G.v.B.: M.D., lecturer in ophthalmology, 31 years of age; observations with the left eye; in this eye hyperopia 0.5 D., regular astigmatism 1 D., visual acuity without correction (as in the experiments) = 0.8, after correction 1.0; green-red coefficient 0.945.

H.E.: M.D., assistant professor in physiology, 48 years of age; determinations with left eye; in this eye hyperopia 1 D., visual acuity without

[25] G. F. Göthlin, *Handb. d. biol. Arbeitsmethoden, herausgeg. v. E. Abderhalden*. Abt. 5, Part 6, Section 931 (Berlin, 1926).

correction (as in the experiments) = 1.4; green-red coefficient 1.014.

N.T.: M.D., lecturer in physiology, 31 years of age; in left eye, the one used in the experiments, hyperopia 0.5 D. and regular astigmatism 1 D., visual acuity without correction (as in the experiments) = 0.8, after correction 1.0; green-red coefficient 0.936.

The observations of the color thresholds and the calculated corresponding energy values are recorded in Tables I and II.

Of the eight series of observations two are reproduced diagrammatically to facilitate survey, the one—Fig. 3—giving the results in a field of 3°, the other—Fig. 4—in a field of 45′.

Although not relevant to the main experiments a unique observation made by observer N.G.A. may be added, since it exhibits an unexpected and completely convincing corroboration of the chief results arrived at in the systematic experiments. In Table I, on reporting the observations of N.G.A. when testing the wave-lengths 435, 440, 445, and 450 mμ, attention is drawn in the "Remarks" to a difference in hue in different parts of the field of observation. This gave cause for the experiment described below.

Observation 25/6/1942.

The subject N.G.A. was tested after an hour's adaptation to total darkness with radiation of wave-length 445 mμ in a field of 5°. The threshold for the perception of light was reached at an energy value of 0.44. When the brightness of the light was increased during exclusive use of the polarization system, a blue threshold sensation, homogeneous for the whole field, was reached at an energy value of 9.2. On further increase of brightness the field assumed the following appearance at the energy value 54.2 when fixed centrally: In the central part, corresponding to about two-thirds of the radius of the lighted field, the color is clear violet; around this zone a rather narrow, brighter ring of less pure violet; outside this the same blue sensation which filled the whole field at the energy value 9.2. When the brightness of the field is still further increased, the central violet is seen to increase simultaneously in scope; its outer boundary moves centrifugally, thus pushing the blue nearer and nearer to the periphery; this continues until at the energy value 365 the sensation is clear violet over the whole field.

A statistical check was applied to find out what degree of certainty is attributable to the threshold settings in the chief series, and what conclusions can be regarded as justified concerning the different positions of the thresholds for blue and red which were registered for the three subjects N.G.A., R.B., and H.E. With this in view each of them was asked to carry out—with a 3° field of observation and N.G.A. with a 45′ field as well—a series of determinations of the blue and red component thresholds for a single wave-length. Such a series, however, tends soon to cause fatigue, particularly when it is performed with foveal field, and it ought not to be continued after marked symptoms of fatigue have made their appearance. For this reason it had been impossible to obtain a longer series than seven or eight pairs of determinations. After this the series had to be interrupted on

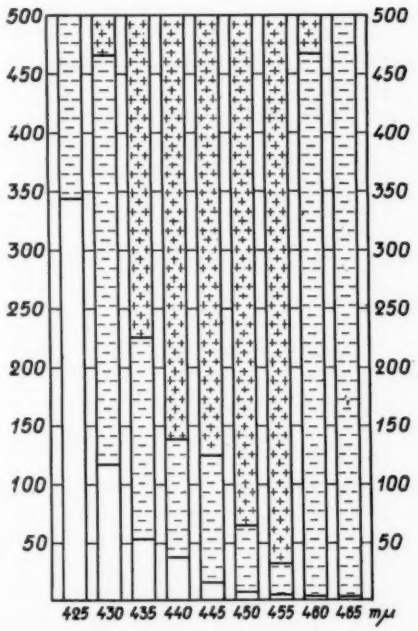

FIG. 4. Diagrammatic representation of the relative energy values of the thresholds for a blue and a red component in spectral indigo, in accordance with determinations by observer N.G.A. Field 45′. The significance of the horizontal lines and the crosses inside the columns is the same as in Fig. 3.

TABLE III. Serial alternating settings of the threshold for a blue component and for a red component in a radiation of spectral indigo. The settings are given in relative energy values.

N.G.A. Field 3°, 445 mμ		R.B. Field 3°, 440 mμ		H.E. Field 3°, 435 mμ		N.G.A. Field 45′, 445 mμ	
Blue component	Red component	Blue component	Red component	Blue component	Red component	Blue component	Red component
34.30	87.53	19.48	33.26	104.1	385.8	41.77	88.64
34.74	104.83	18.89	41.78	78.55	354.7	41.93	118.5
35.41	60.56	13.72	39.08	95.28	372.8	27.71	98.74
29.95	74.26	14.68	50.0	94.83	402.7	47.06	79.08
47.92	70.37	13.14	40.98	88.08	333.9	61.13	78.23
36.23	79.29	13.99	48.90	117.9	395.1	37.99	100.7
28.59	88.30	13.45	40.84	83.79	407.6	58.68	109.1
		14.34	47.36	130.3	400.5		

TABLE IV. Tabular survey of the statistical treatment of the threshold values in Table III.

Observation field / Observer / Wave-length / n		3° (macular field) H.E. 435 mμ 8	3° (macular field) R.B. 440 mμ 8	3° (macular field) N.G.A. 445 mμ 7	45′ (foveal field) N.G.A. 445 mμ 7
T_1	$m\pm\epsilon(m)$	99.1±6.21	15.2±0.88	35.3±2.36	45.2±4.42
	σ	17.57	2.50	6.25	11.69
	v	17.7%	16.4%	17.7%	25.8%
T_2	$m\pm\epsilon(m)$	381.6±9.20	42.8±1.99	80.7±5.44	96.1±5.70
	σ	26.02	5.64	14.39	15.08
	v	6.8%	12.3%	17.8%	15.7%
T_2-T_1	$m\pm\epsilon(m)$	282.5±8.39	27.6±2.54	45.4±6.58	51.0±8.05
	σ	23.72	7.17	17.41	21.29
	v	8.4%	26.0%	38.3%	41.8%
$(T_2-T_1)/T_1$	$m\pm\epsilon(m)$	2.93±0.209	1.89±0.221	1.34±0.232	1.28±0.295
	σ	0.591	0.624	0.613	0.780
	v	20.2%	33.0%	45.1%	60.8%
T_1/T_2	$m\pm\epsilon(m)$	0.259±0.0139	0.365±0.0365	0.453±0.0505	0.485±0.0642
	σ	0.0392	0.1033	0.1336	0.1698
	v	15.1%	28.3%	29.5%	35.0%

account of beginning symptoms of fatigue. The threshold energies in these series are given in Table III.

The statistical treatment of these values has been carried out by Dr. H. Enghoff and gives the results shown in Table IV.

$$v = \text{coefficient of variation} = 100\sigma/m.$$

It can be seen from the table that the coefficient of variation for the threshold of the red component in a 3° field of observation for two of the observers, R.B. and H.E., and for N.G.A. in a 45′ field of observation, is lower than the corresponding coefficient for the blue threshold. In none of the cases is the difference between the coefficients of variation statistically significant, but the degree of probability that such a difference is present in H.E. can be put as high as 0.95–0.98. It looks, therefore, as if the determination of the red component threshold is relatively no more difficult than the determination of the blue threshold.

It may also be seen from the table that the mean for the quantities T_2-T_1 and $(T_2-T_1)/T_1$ in all four control series, even when the small number of the observations is taken into consideration, must without doubt be considered significant. In other words, there is a fully confirmed average relative as well as absolute difference between the red component threshold and the blue threshold. The same seems to be true of the separate observations of relative threshold differences at various wave-lengths in foveal vision with subject N.G.A., insofar as one dares assume that the standard deviation found for wave-length 445 mμ can also be used as the

basis for estimating the differences in the same subject at the other wave-lengths investigated. On the same condition, all the relative threshold differences—with one exception (430 mμ)—obtained with subject R.B. in macular vision are also significant.

Further, the averages for the quotient T_1/T_2 in all four control series prove to be significant. But under certain conditions this quotient can be regarded as supplying a relative measurement for the proportion between the red and blue components in the complex sensation of indigo. By studying T_1/T_2, therefore, one should be able to determine whether, within the wave-length region which corresponds to indigo, there is a definite quantitative relationship between the wave-length and the proportion of red to blue in the sensation. In the six pairs of observations made in macular field within the wave-length region 455–430 mμ by subject R.B., such a relationship appears. The quotient T_1/T_2 decreases as the wave-length increases (cf. Table I). The quantitative relationship seems to be best expressed in this case by means of an equation of the type

$$y=\alpha \exp(-Bx^2+\gamma x),$$

where y denotes the quotient T_1/T_2 and x the wave-length, and geometrically by means of the corresponding curve in Fig. 5.

The root mean square error is, in percentage, of the same order of magnitude as the standard deviation for the quotient T_1/T_2 in the corresponding control series of the same subject with a field of 3°. With regard to the differences in the single determinations between the calculated and the observed values, the reader is referred to Fig. 5.

Assuming that the two components in indigo are present in the color sensation in inverse proportion to their respective threshold values, the amount of red in proportion to blue will in the case of R.B. contain, with decreasing wave-length, a continuously increasing proportion of red. On the assumption made above the proportion of the red component in the sensation at 455 mμ is only $(32/1032)\times 100=3.1$ percent, but at 430 mμ it has risen to $(441/1441)\times 100=30.6$ percent that is, about 10 times as much.

4. CONCLUSIONS

At the beginning of Section 2, the consequences of the assumption that the short wave fundamental color is violet and that a color-threshold determination could take place in the compound sensation of indigo were described. In the experiments these consequences have not appeared. With no subject and no wave-length within the indigo region was the threshold for violet or green obtained at a lower brightness, and a threshold for a more bluish color only at a higher brightness. On the other hand, the exact opposite happened in an individually varying number of wave-lengths with some of the subjects. With three out of five of them it was found that throughout the whole or nearly the whole of the indigo region, when the radiant flux was increased from 0, a color threshold for blue was reached at a lower flux, while only at a higher flux did a red component begin to be discernible and add itself to the already present blue to form that special type of violet which Newton called indigo.

The fact that the mode of separation of the color threshold in these cases reveals exactly what would happen if the short wave fundamental color were blue, justifies *the conclusion that blue has its own receptors and that the short wave fundamental color is blue.*

One of the remaining subjects, G.v.B., observed the separation into a threshold for blue

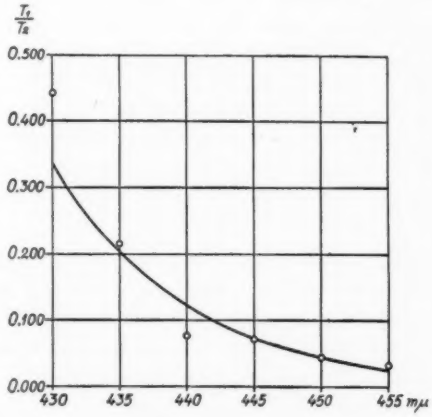

FIG. 5. Diagrammatic representation of the dependence of the quotient T_1/T_2 on the wave-length according to determinations in spectral indigo by observer R.B. Field 3°.

and a threshold for red for a few wave-lengths only. The fifth subject, N.T., observed no separation. In individuals of N.T.'s type, the thresholds for the components seem to coincide or, at all events, to lie so close together that they cannot be distinguished experimentally. On account of the individual differences now described it is tempting to assume some kind of enforced collaboration, firmer in some individuals than in others, between the receptors for blue and the receptors for red, when they are affected by radiations from the indigo-violet region of the spectrum. To discuss this question in a thoroughgoing fashion lies, however, outside the scope of this experimental investigation.

Evidence in support of the chief result of my series of color-threshold analyses is provided by the perception defect met with in spectroscopically investigated cases of tritanopia. A survey of such cases, collected from the literature by the author,[26] shows that of the two most typical cases of this color sense so far described, the one perceived all short wave visible radiations below 452 mμ as "red with a lot of small black spots," the other all radiations with wave-lengths from about 477 to about 416 mμ as a "thin red." Consequently, violet and at least part of the indigo region take on the character of red when the short wave fundamental color is absent.

The fact that blue is the short wave fundamental color entails another conclusion. In order to determine the course of the curves for the exciting effect of the spectral radiations on the different color receptors, the three-color synthesis should be expressed in terms of a primary of a more long wave and purer blue than in the experimental series of Maxwell (where it amounted to 457 mμ) and in that of W. D. Wright (where it amounted to 460 mμ).

SUMMARY

On analyzing with the present writer's liminospectroscope in five subjects with normal color vision and accustomed to colors the color thresholds for spectrally homogeneous radiations of the wave-lengths 430, 435, 440, 445, 450, and 455 mμ in spectral indigo, the following results were established.

When the radiant flux entering eyes adapted to total darkness in a central field of 3° or 45′ was continuously increased from 0, the first color sensation which appeared in four subjects for a series of radiations was blue. At a radiant flux in most cases several times higher, a sensation of a red component emerged. In three subjects the continuous series of wave-lengths with color thresholds separable in this way contained all or nearly all the wave-lengths chosen in the indigo range, but in one subject only a narrower series of them. In serial settings with only one radiation the difference in threshold values of the blue and the red sensation proved in the three subjects to be statistically significant. Moreover, the determination of the red component threshold appeared to be relatively no more difficult than the determination of the blue threshold. In a fifth subject no dissociation of the color threshold was discernible. In no observer did a sensation of violet or of green precede a bluish sensation, as would have been the case if blue were built up, in accordance with the hypothesis of Wünsch, Young, and Helmholtz, by simultaneous impulses to green and to violet and a dissociation of the color threshold took place.

By the series of color-threshold observations here presented, it is experimentally settled that in man's normal color sense blue has its own receptors and is identical with the short wave fundamental color, the existence of which the three-color hypothesis assumes, while violet is *not* a fundamental color with special receptors. This last conclusion is supported by the established fact that in the purest cases of congenital tritanopia the radiations of spectral violet release a sensation of color in which *only red* is perceived.

There exist individuals with normal color sense to whom a cleavage of the color threshold in indigo is not perceivable. Even in subjects able to distinguish different thresholds of two components in indigo, this may probably not be displayed without access to an instrument with extremely fine arrangements for regulation of light flux, and when the eyes are sensitized by protracted adaptation to total darkness.

[26] G. F. Göthlin, Acta Ophthal. (Copenhagen) **21**, 88 (1943).

A Quantitative Formulation of Color Mixture and Chroma Discrimination Data for Dichromats*

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THE formulation of data presented in this paper was undertaken with two aims in mind: (1) to organize the data so that they might be used in a quantitative way to determine whether it is valid to use a chromaticity diagram for a normal trichromat as Pitt[1] and Judd[2] have done to classify confusion colors for dichromats, and (2) to organize the chroma discrimination data in a form in which they would be most useful in gaining an insight into the underlying physiological mechanisms.

I. COLOR MIXTURE

An Equation for Color Mixture Data for Dichromats

Color mixture data for dichromats are characterized by the fact that the various spectral stimuli can be matched by mixtures of two properly chosen primaries. The color mixture data for two dichromats which were investigated by Hecht and Shlaer[3] are shown in Fig. 1. Hecht and Shlaer employed for their primaries blue and yellow spectral stimuli whose wave-lengths are 458.7 mμ and 570.0 mμ. The data have been analyzed so that the intensities of the two primaries are expressed in energy units. The ordinate values represent the percentage P of blue in the distimulus match. Since the sum of the percentages of the two primaries is always equal to 100, it is not necessary to specify the percentage of yellow. The abscissae values represent wave-length λ.

For various mixtures Hecht and Shlaer determined the range of spectral stimuli that appeared to match, and the two solid curves in each graph represent the spectral limits of the matches. An intermediate dotted curve has been drawn in for both the protanope and the deuteranope to represent the midpoint of the matching zone in a vertical direction. The vertical distance across the zone is much more constant than the horizontal distance and it is more justifiable, therefore, to choose the midpoint of the zone measured in the vertical direction. It would probably be more satisfactory for the problem at hand to carry out the experiment by keeping the wave-length constant and varying the percentages of blue and yellow in the mixture. At least the data at the two ends of the curve would be more significant.

The dotted curves conform reasonably well to the following equation:

$$P=\frac{100}{1+10^{K(\lambda-C)}}. \qquad (1)$$

In this equation the constant K is a function of the slope of the curve at the 50 percent level and is the same for both dichromats, namely, 0.0465. C is the point on the wave-length scale at which the curve crosses the 50 percent level. This point is 488 mμ for the protanope and is 503.5 mμ for the deuteranope.

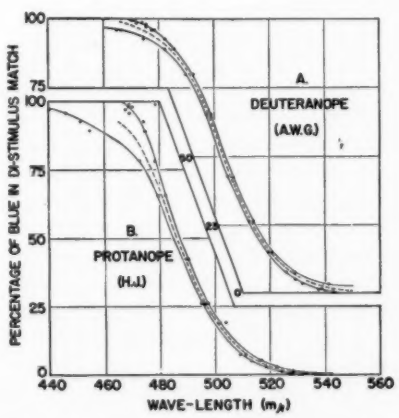

FIG. 1. Color mixture data for two dichromats obtained by Hecht and Shlaer. The two primaries are 458.7 and 570.0 mμ and their intensities are expressed in energy units.

* Paper presented at the Twenty-Eighth Annual Meeting of the Optical Society of America, Pittsburgh, Pennsylvania, October 7–9, 1943.

[1] F. H. G. Pitt, "Characteristics of dichromatic vision," Medical Research Council, Special Report No. 200 (1935).

[2] D. B. Judd, J. Opt. Soc. Am. **33**, 305 (1943).

[3] S. Hecht and S. Shlaer, J. Gen. Physiol. **20**, 57–93 (1937).

In accordance with Eq. (1) the dotted lines in Fig. 1 if extended would be asymptotic to the 0 and 100 percent levels. Had the data been obtained by measuring the limits of the matching zone by varying the percentages in the mixture

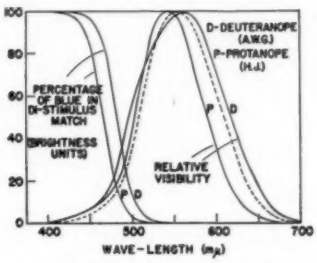

FIG. 2. Color mixture and visibility data for H.J. and A.W.G. The visibility data for the I.C.I. observer (dotted curve) are included for comparison.

instead of the wave-length of the spectral color, it would be possible to determine to what extent the equations are in error near these levels, but on general principles one might expect the dotted curves to cross the 0 and 100 percent lines at the two primaries. These difficulties could have been avoided completely if the necessary measurements had been made to translate the data into terms of primaries at the extreme ends of the spectrum. If the primaries were located at the two extreme ends of the spectrum, it would make little difference whether the empirical curves cross or become asymptotic to the 0 and 100 percent lines.

Color Mixture Data Expressed in Brightness Units

Changing from energy units to brightness units merely changes the value of C in Eq. (1); and the dotted curves in Fig. 1 do not change shape but are merely shifted in a lateral direction.

If we let E_Y and E_B represent the intensities of the yellow and blue primaries expressed in energy units, and if we let C_E represent the value for C when the two primaries are expressed in energy units, and if we solve Eq. (1) for the term $10^{K(\lambda - C_E)}$,

$$10^{K(\lambda - C_E)} = \frac{100 - P}{P} = \frac{E_Y}{E_B}. \qquad (2)$$

In order to express the intensities of the two components in brightness units it is necessary to multiply the energy of the yellow component E_Y by the visibility function for yellow V_Y and the energy of the blue component E_B by the visibility function for blue V_B.

Hence, when the intensities of the two components are expressed in brightness units

$$P = \frac{100}{1 + \frac{V_Y}{V_B} 10^{K(\lambda - C_E)}} = \frac{100}{1 + 10^{K[\lambda - C_E + (\log V_Y/V_B)/K]}}. \qquad (3)$$

The term

$$\left[C_E - \frac{\log (V_Y/V_B)}{K} \right]$$

is merely an expression for C in Eq. (1) when the intensities of the two primaries are expressed in brightness units.

The color mixture curves based on the use of brightness units for the intensities of the two primaries are shown in Fig. 2. The values for V_Y and V_B were obtained from the visibility curves which are included in the same figure. (See also Table I.) The new values for C for H.J. and A.W.G. are 465.0 and 482.5, respectively.

One advantage in using brightness units instead of energy units is that the data are independent of the choice of primaries so long as the primaries lie in the outer regions of the spectrum where wave-lengths cannot be discriminated from each other.

Spectral Matches for Heterochromatic Stimuli

Another advantage in expressing the color mixture data in brightness units is that in this form the data can be used for computing spectral matches for heterochromatic stimuli. The procedure is as follows: First, a spectrophotometric analysis is made of the stimulus to obtain an energy distribution. This is translated into luminosity units by making use of the visibility curve for the given individual. The visibility curves for A.W.G. and H.J. are included in Fig. 2. In the absence of visibility data for a given dichromat the standard visibility curves for deuteranopes and protanopes proposed by

Judd[4] might be employed. The ordinate values of the luminosity curve are then multiplied by the percentages of blue required to match the wave-lengths in question and divided by 100 and another curve is obtained. The ratio of the area under this curve to the area under the luminosity curve multiplied by 100 represents the percentage of blue in the distimulus match. The spectral match can then be determined directly from the color mixture curve.

The Neutral Point in the Dichromat's Spectrum

For the purpose of this paper, the neutral point is arbitrarily defined as the point in the spectrum which matches a white stimulus whose color temperature is 5000°K. Hecht and Shlaer determined this point directly by comparing such a white with the various spectral colors, and found it to lie at 491.5 mμ for the protanope and at 495.0 mμ for the deuteranope.

One should be able to predict the neutral point from the visibility data and the color mixture data by making use of the procedure described above for calculating the spectral match for a heterochromatic stimulus. The relative energy distribution curve for a Planckian radiator at 5000°K is shown as curve E in Fig. 3. The luminosity curve L for this stimulus for the protanope (H.J.) was obtained by multiplying the ordinates of the energy distribution curve by the ordinates of the relative visibility curve in Fig. 2 and dividing by 100. The curve B in Fig. 3 was obtained by multiplying the ordinates of curve L by the ordinates of the color mixture curve in Fig. 2 and dividing by 100. The ratio of the area under this curve B to the area under the luminosity curve L when multiplied by 100 represents the percentage of blue in the distimulus match and was found to be 3.2. The predicted neutral point is, therefore, 498.0 mμ.

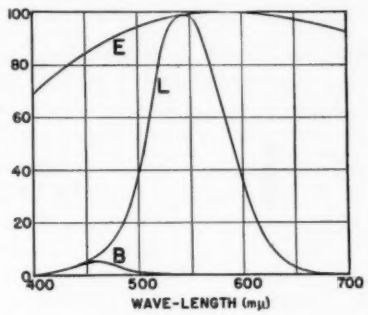

FIG. 3. Curves used in computing the neutral point for H.J. Curve E represents the energy distribution for the white stimulus (5000°K) and curves L and B represent the corresponding brightness distribution and blue component curves for H.J.

Using the same procedure for the deuteranope the predicted neutral point was found to be 508.5 mμ. The data that form the bases for these predictions are shown in Table I.

The predicted neutral points lie closer to the red end of the spectrum than the ones determined by direct comparison, but no explanation has been found for this discrepancy. The visibility data as well as the color mixture data, which are used in the calculation of the neutral point, involve a certain lack of precision on the part of the subject, but the nature of these errors makes it difficult to demonstrate whether the discrepancy lies within the margin afforded by them.

TABLE I. Data used in computing the spectral match for white (5000°K).

λ	E	Protanope (H.J.) V	L	P	B	Deuteranope (A.W.G.) V	L	P	B
400	69.0	00.0	00.0	100.0	.0	00.0	00.0	100	.0
410	72.7	01.0	00.7	100.0	.7	01.0	00.7	100	.7
420	76.0	02.0	01.5	99.0	1.5	02.0	01.5	100	1.5
430	79.1	03.5	02.8	98.0	2.7	03.5	02.8	100	2.8
440	82.3	05.0	04.1	94.0	3.9	05.0	04.2	99	4.2
450	85.0	06.5	05.5	84.0	4.6	07.0	06.0	97	5.8
460	87.2	09.0	07.0	65.0	5.1	10.0	08.7	91	7.9
470	89.7	12.5	10.9	39.0	4.3	15.0	13.5	79	10.6
480	91.7	17.5	16.0	19.0	3.0	24.0	22.0	57	12.5
490	93.4	27.5	25.7	7.0	1.8	40.0	37.4	31	11.5
500	94.9	42.0	39.8	2.5	1.0	56.0	53.1	14	7.4
510	96.3	64.0	61.6	1.0	0.6	69.0	66.4	5	3.3
520	97.3	83.0	80.8	0.0	.0	78.0	75.9	2	1.5
530	98.1	96.0	94.2			86.5	84.9	1	0.8
540	98.8	100.0	98.8			93.5	92.3	0	.0
550	99.5	99.0	98.5			98.0	97.5		
560	99.9	92.0	91.9			100.0	99.9		
570	100.0	79.0	79.0			99.0	99.0		
580	100.0	65.0	65.0			93.5	93.5		
590	99.9	49.0	49.0			83.0	83.0		
600	99.9	35.0	35.0			73.0	73.0		
610	99.3	24.0	23.8			60.0	59.6		
620	98.8	15.0	14.8			47.0	46.4		
630	98.3	08.5	08.4			35.0	34.4		
640	97.6	05.0	04.9			25.0	24.4		
650	96.8	03.0	02.9			16.0	15.5		
660	96.3	01.5	01.4			10.0	09.6		
670	95.1	00.5	00.5			05.0	04.7		
680	94.1	00.2	00.2			03.0	02.8		
690	93.1	00.0	00.0			02.0	01.9		
700	92.2	00.0	00.0			01.0	00.9		
Sum			925.5		29.2		1215.5		70.5
P value of the distimulus match for white.				$100\frac{29.2}{925.5}=3.16$				$100\frac{70.5}{1215.5}=5.80$	
Spectral match for white.				498 mμ				508.5 mμ	

[4] D. B. Judd, reference 2, pp. 303–304.

Confusion Colors for Dichromats

As Pitt[5] pointed out, an important application of the procedure described above is the determination of confusion colors for dichromats. Any two stimuli which have the same spectral match constitute confusion colors for a dichromat.

It is also possible to determine the tristimulus coefficients for a dichromat's confusion colors and plot them on a chromaticity diagram for a normal trichromat. This is useful to the extent that it gives some indication of the capacity of a trichromat to differentiate colors that appear identical to the dichromat.

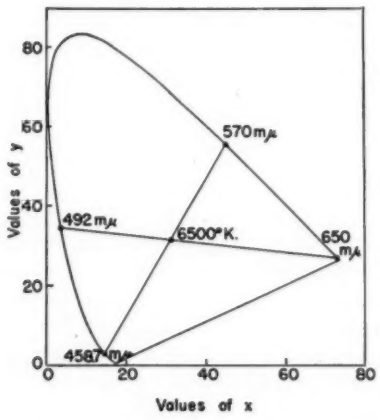

FIG. 4. Mixtures of complementaries which appear alike to the standard I.C.I. observer but quite unlike to the protanope A.W.G.

Pitt[6] and Judd[7] also claim that the chromaticity diagram can be marked off into zones and used to pick out confusion colors for dichromats. In order for this relationship to exist, one condition that has to be filled is that any two stimuli that have the same tristimulus coefficients must appear alike to the dichromat. In the case of the standard I.C.I. observer, for example, wavelengths 492 mμ and 650 mμ mixed in an energy ratio of 0.89 to 1 constitute a match for a 0.687 to 1 mixture of 458.7 mμ and 570.0 mμ. Both mixtures match white (6500°K) and are plotted at the same point on the I.C.I. chromaticity diagram. (See Fig. 4.) Calculations show that the dichromat A.W.G. would match the yellow-blue mixture with 507 mμ and the red-green mixture with 497 mμ. These two points in the spectrum are about 22 J.N.D. steps apart for this particular dichromat.

Pitt claimed that any instance in which a color match for a trichromat fails for a dichromat can probably be accounted for in terms of the effects of macular pigmentation. It has not been determined to what extent this is possible in the case of A.W.G. It is true that A.W.G.'s visibility curve deviates on the blue side from that of the I.C.I. observer, which corresponds closely to that of the average deuteranope.

The match is somewhat more satisfactory for H.J. since the distimulus match for the blue-yellow mixture is 491.5 and that for the red-green mixture is 492.5 mμ.

Pitt's Color Mixture Data

Pitt[8] obtained data for eight protanopes and seven deuteranopes. The data for all of the protanopes and one of the deuteranopes were obtained with blue (460 mμ) and green (530 mμ) primaries. The data for six of the deuteranopes were obtained, however, with blue (460 mμ) and red (650 mμ) primaries. The data obtained with the blue and green primaries were transformed to give coefficients in terms of the blue and red primaries. Pitt's average curves for protanopes and deuteranopes are presented in Fig. 5. In Pitt's original graph the 100 percent level intercepted the curves at a wave-length value of 460, but the percentage scale in Fig. 5 has been magnified to make the curves asymptotic to the 100 percent level. This is equivalent to changing the blue primary from 460 to 430 mμ.

The curve for the deuteranope conforms quite well to Eq. (1), when K is assigned a constant value of 0.0425 and C a constant value of 494. The K value agrees reasonably well with that of the dichromats of Hecht and Shlaer. A C value of 494 was obtained because arbitrary units were used for the primaries, and these were varied from subject to subject to keep the half-and-half mixture of the two primaries matching 494 mμ.

The average curve for Pitt's protanopes deviates a little from the deuteranopic curve at the

[5] F. H. G. Pitt, reference 1, p. 45.
[6] F. H. G. Pitt, reference 1, pp. 45–50.
[7] D. B. Judd, reference 2, p. 305.
[8] F. H. G. Pitt, reference 1, pp. 9–17.

red end of the spectrum, but the agreement with Eq. (1) can probably be regarded as satisfactory when the same constants are used as for the deuteranope.

Pitt states that an average red-blue brightness ratio of 1 to 0.062 was required by the deuteranopes to match 494 mμ, and that the average ratio was 1 to 0.071 for the protanopes. The C value which is obtained when the intensities are expressed in brightness units can, therefore, be calculated in accordance with the following formula:

$$C = 494 - \frac{\log_{10}(\text{brightness ratio required to match 494})}{0.0425}.$$

It was found to be 465.6 for the average deuteranope and 467 for the average protanope. In view of these data A.W.G.'s C value of 482.5 appears to be somewhat atypical for a deuteranope and it cannot be argued that the C value for the average deuteranope differs significantly from that of the average protanope.

A Short Method for Determining the Value of C

If when additional data are analyzed it can be demonstrated further that K does remain relatively constant from one dichromat to another, C would be the only value that would have to be determined in a given case to obtain a complete set of color mixture data. The value for C could be obtained quickly with an instrument like the anomaloscope in which, say, wave-lengths of 460 and 570 mμ are employed as the primaries and a wave-length in the region of 500 mμ is used as the test color. The energy ratio of the two primaries required to match the test color could be translated quickly into the C value, because it follows from Eq. (2) that when $\lambda = 500$,

$$C_E = 500 - \frac{1}{K}\left(\log_{10}\frac{E_Y}{E_B}\right). \qquad (4)$$

The same test would provide a means for differentiating dichromats from anomalous trichromats, because anamalous trichromats would not be able to make the match.

II. CHROMA DISCRIMINATION

Pitt,[9] and Hecht and Shlaer,[10] among others, have more or less established the custom of expressing the chroma discrimination data of dichromats in terms of J.N.D. (Just Noticeable Difference) steps on a wave-length scale. The data of Hecht and Shlaer can be readily transformed into terms of J.N.D. steps on a color mixture diagram which in the case of a dichromat represents a straight line connecting two spectral primaries located near the two ends of the spectrum.

The advantage in transforming the data from a wave-length scale to a color mixture scale is that they constitute in the latter form a more effective probe for gaining insight into the nature of the physiological mechanisms subserving the color vision of a dichromat; that is to say, the most promising inroad into this domain of the unknown is to inquire, first, why and how different mixtures of two primaries produce a variety of color sensations, and, secondly, how it is possible for the various spectral stimuli to produce equivalent results. This approach to the problem eliminates altogether the need for the consideration of wave-length discrimination data as such.

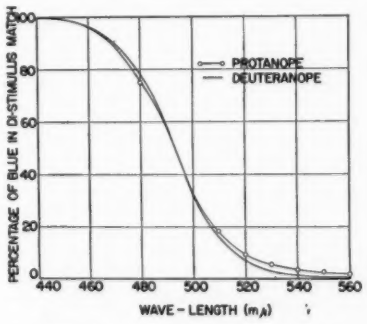

FIG. 5. Pitt's color mixture data.

The wave-length discrimination data of Hecht and Shlaer for the deuteranope A.W.G. have been transformed from terms of λ into terms of P in accordance with Eq. (1) and are plotted in Fig. 6. The solid dots represent J.N.D. steps toward the red end of the scale and the open

[9] F. H. G. Pitt, reference 1, pp. 25–31.
[10] S. Hecht and S. Shlaer, reference 3, pp. 60–65.

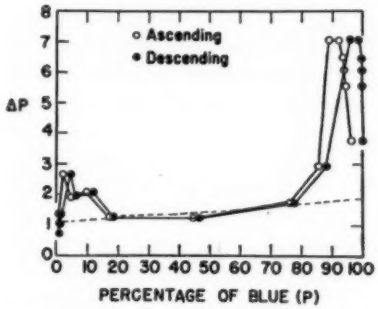

FIG. 6. Chroma discrimination data for the deuteranope A.W.G. The intensities of the two primaries are expressed in energy units.

circles toward the blue end. (The original data in terms of $\Delta\lambda$ and λ are to be found in Table I on p. 63 of the paper by Hecht and Shlaer. The set of data used in Fig. 6 represents the set obtained in May, 1931.)

The maxima at the red and blue ends of the scale probably represent systematic errors of some sort, either in acquiring or in analyzing the data, but this cannot be determined without further experimentation. An instrument similar to the one described by MacAdam[11] would greatly simplify the procedure in acquiring data of the sort in question, because in MacAdam's instrument, P is varied to measure the chroma sensitivity, and the intensities of the two stimuli are automatically kept equal. The filters employed would have to have transmissions restricted one to one end and the other to the other end of the spectrum and the intensities would have to be specified in brightness units.

In attempting to formulate and fit an equation to represent ΔP as a function of P, the maxima at the ends of the scale have been ignored. The dotted curve in Fig. 6 corresponds to the following equation:

$$\Delta P=\frac{100}{N\phi}\left[1+\frac{P(\phi-1)}{100}\right]^2. \tag{5}$$

The ΔP values, 1.7 corresponding to $P=80$ and 1.2 corresponding to $P=20$, were used in calculating N and ϕ. These were found to be 67.5 and 1.3, respectively.

If we define S as the number of J.N.D. steps from the red end of the chroma scale,

$$S=\int_0^P \frac{N\phi}{100}\left[\frac{1}{1+P\left(\frac{\phi-1}{100}\right)}\right]^2 dP$$

$$=\frac{N}{1+\left(\frac{100-P}{P}\right)\left(\frac{1}{\phi}\right)}. \tag{6}$$

The constant N in Eqs. (5) and (6) represents the total number of J.N.D. steps in the chroma scale, because when $P=100$,

$$S=N.$$

Equation (6) can be simplified by weighting the intensity of the red primary by multiplying it by ϕ. This is accomplished in the case of Eq. (6) by multiplying the term $(100-P)/P$ by ϕ; because

$$\frac{100-P}{P}=\frac{\text{intensity of the red primary}}{\text{intensity of the blue primary}}.$$

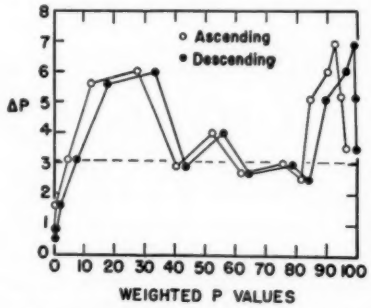

FIG. 7. Chroma discrimination data for the protanope H.J. The intensities for the two primaries were originally expressed in energy units, but the P values have been weighted by multiplying the intensity for the yellow primary by 4.4.

Therefore, in terms of the weighted primaries,

$$S=\frac{N}{1+\frac{(100-P)\phi}{P}\left(\frac{1}{\phi}\right)}=\frac{NP}{100}, \tag{7}$$

and

$$\Delta P=\frac{100}{N}. \tag{8}$$

This means so far as the equation goes that the J.N.D. steps in percentage units are uniform

[11] D. L. MacAdam, J. Opt. Soc. Am. **32**, 247–274 (1942).

at the different percentage levels. ϕ may be defined, therefore, as the factor by which the intensity of the red primary must be weighted to produce a color mixture scale with uniform J.N.D. steps, or as nearly so as possible. The value for ϕ will vary depending on whether the intensities are expressed in energy or brightness units.

The wave-length discrimination data of Hecht and Shlaer for the protanope H.J. were also transformed from terms of λ to terms of P and plotted on a graph similar to Fig. 6. The original data in terms of λ and $\Delta\lambda$ are contained in Table I on p. 63 of the paper by Hecht and Shlaer. The set of data used was that obtained in May, 1933. The ϕ and N values were determined from this graph to be 4.4 and 32.8, respectively.

The data were then reanalyzed in terms of weighted P values. The following equation was used in converting from unweighted to weighted P values:

$$\text{Weighted } P \text{ value} = \frac{1}{1+\dfrac{100-P}{P}\phi}. \qquad (9)$$

The final results are plotted in Fig. 7. We find in this graph also maxima at the two ends of the scale but, as explained in connection with the data for A.W.G., such maxima probably depend upon systematic errors.

It is possible as shown below to derive from Eq. (6) an equation for $\Delta\lambda$ as a function of λ.

Since it is possible to select a point H on the wave-length scale which bears the following relation to ϕ, K, and C,

$$\phi = 10^{K(H-C)}, \qquad (7)$$

and since from Eq. (2),

$$\frac{100-P}{P} = 10^{K(\lambda-C)}$$

Eq. (6) becomes:

$$S = \frac{N}{1+10^{K(\lambda-H)}}. \qquad (8)$$

By differentiation,

$$\Delta\lambda = \frac{\log_{10} e}{KN}[10^{K(\lambda-H)}+10^{K(H-\lambda)}+2]. \qquad (9)$$

In Fig. 8 the original data for H.J. and A.W.G. in terms of λ and $\Delta\lambda$ have been plotted, and the dotted curves which conform to Eq. (9) have been drawn in for comparison.

The H values of 501.8 mμ for H.J. and 506 mμ for A.W.G. correspond to the ϕ values of 4.4 and 1.3 for the dotted curves in Figs. 6 and 7. The N values are the same as for the dotted curves in Figs. 6 and 7.

In each graph, the ordinate corresponding to

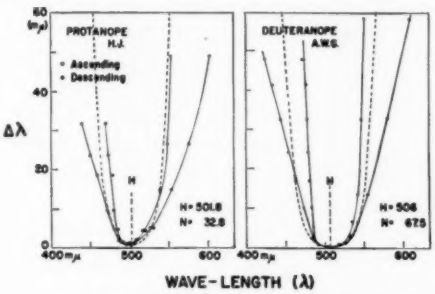

FIG. 8. Wave-length discrimination data for A.W.G. and H.J.

H represents an axis of symmetry. Increasing the value of H which is equivalent to increasing the value of ϕ shifts the whole curve to the right.

According to the equation the minimum $\Delta\lambda$ value is obtained when λ is equal to H, and in this case,

$$\Delta\lambda = \frac{4\log_{10} e}{KN}, \qquad (10)$$

and since K is constant, the minimum value for $\Delta\lambda$ is entirely dependent on N. Decreasing the value of N gives rise to a series of U-shaped curves, each new curve fitting inside its predecessor.

Whereas the theoretical curves are symmetrical, the data for H.J. are not symmetrical and, to a slight extent, this is also true for A.W.G. Many of Pitt's[12] subjects also showed asymmetry but always in the opposite direction from H.J.

Figure 8 also indicates that a better fit would be obtained if the value for K could be increased to make the U-shaped curves more pointed.

[12] F. H. G. Pitt, reference 1, pp. 25–31.

An increase in the value for K would also reduce the maxima at the two ends of the curves in Figs. 6 and 7, and furthermore, it would shift the calculated spectral matches for white closer to the ones found by direct comparison.

III. SUMMARY

The essential facts regarding color mixture and chroma discrimination for dichromats may be summarized as follows:

(1) Any of the spectral colors or mixtures thereof can be matched by mixtures of two spectral primaries located near the two ends of the spectrum.

(2) The percentage P of blue in the mixture of red and blue primaries required to match the various spectral colors λ can be expressed in terms of the following equation:

$$P=\frac{100}{1+10^{K(\lambda-C)}}.$$

The intensities of the two primaries can be expressed in terms of either energy or brightness units; changing from one to the other merely changes the value of the constant C. The constant K remains relatively constant from one dichromat to another. When the intensities of the two primaries are expressed in brightness units, C is also relatively constant, the average for Pitt's protanopes being 467 and the average for his deuteranopes being 465.6 mμ.

The value for the deuteranope A.W.G., however, was found to be exceptionally large, namely, 482.5 mμ.

(3) The use of the above formula in determining the spectral match for a heterochromatic stimulus of known wave-length composition has been described. This procedure has been used for calculating the spectral match for white from the color mixture and visibility data. This was then compared with the match determined by direct comparison.

(4) This procedure has also been employed in testing whether colors of different wave-length composition that appear alike to trichromats also appear alike to dichromats.

(5) A short method for determining the value for C for a given dichromat has been described.

(6) If the intensity of one of the primaries is weighted by a certain factor ϕ, the just perceptible change in the percentage P of blue in the mixture of the two primaries remains relatively constant at the various percentage levels. The total number N of J.N.D. steps in the chroma scale varies for different dichromats. The value for ϕ for the deuteranope A.W.G. is considerably lower than for the protanope H.J., but this is probably due to the fact that A.W.G.'s C value is exceptionally high. Since the H and C values are relatively constant when the intensities of the two primaries are expressed in brightness units, the value for ϕ expressed in brightness units ought also to be constant.

Further Study of ω Space

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INTRODUCTION

THE recent paper[1] by Moon and Spencer presents a three-dimensional Euclidean space in which a unit distance in any direction is intended to represent equal visual color differences. These authors have made use of the latest Munsell data[2] in setting up the transformation from I.C.I. notation to the new ω space.

This paper is concerned with a further study of the ω space. Additional Munsell data have been transformed to the ω space in order to determine with what accuracy the Munsell colorspace is described by the theory. In order to facilitate the comparison of results, a standard adaptation has been chosen. The ω_2 function has been altered slightly to improve the agreement with the recommended data at low values. The relation between hue angle θ and dominant wave-length is investigated. Finally, additional Munsell data have been plotted in the $\omega_2\rho$ planes, and a plot in the $\omega_1\omega_3$ plane has been extended to the higher chromas.

As stated above, the main purpose of this paper is to compare the theory with the Munsell data.[2] In some cases where differences between theory and data exist, the authors are in no position to decide which is the better approach to a uniformly spaced color solid. In a few cases of disagreement, however, the authors do have an opinion and this has then been expressed.

CHOICE OF ADAPTATION

Moon and Spencer[1] have given the relations

$$\omega_1=\frac{2(p_1-0.95p_2)}{0.168(1.63+p_2)^{\frac{1}{2}}-0.119},$$
$$\omega_3=\frac{2.27(p_3-1.10p_2)^{1.2}}{0.628(1.80+p_2)^{\frac{1}{2}}-0.521}. \quad (1)$$

If X, Y, Z are the tristimulus values of the color in question, and X_0, Y_0, Z_0 are the tristimulus values of the background, then

$$p_1=\frac{X-X_0}{Y_0}=\frac{Y(x/y)-Y_0(x_0/y_0)}{Y_0},$$
$$p_2=\frac{Y-Y_0}{Y_0}, \quad (2)$$
$$p_3=\frac{Z-Z_0}{Z_0}=\frac{Y(z/y)-Y_0(z_0/y_0)}{Y_0}.$$

In order to transform from I.C.I. data to ω space, it is necessary to assume a certain adaptation or background. In their paper, Moon and Spencer used the tristimulus values of the neutral gray background used during the study of the Munsell colors, namely, $X_0=19.19$, $Y_0=19.77$, $Z_0=22.10$. In this paper, for reasons given below, all calculations have been made with a background for which $X_0=19$, $Y_0=20$, $Z_0=22$.

As a standard adaptation for purposes of calculation, the most natural one to choose probably would be that having the same chromaticity as I.C.I. Illuminant *C*. This choice would eliminate the uncertainty in hue for near-neutral colors which necessarily results from the selection of any other specification for the adaptation. That is, if the adaptation has a chromaticity different from that for Illuminant *C*, then a color having a chromaticity anywhere on the line joining Illuminant *C* and the adaptation would have a dominant wave-length on the chromaticity diagram and a hue in ω space which are approximately complementary. In other words, if the adaptation is blue, for example, with respect to Illuminant *C*, then a color with a chromaticity between the adaptation and Illuminant *C* would appear blue with respect to Illuminant *C* and yellow with respect to the adaptation.

The choice of Illuminant *C* adaptation, however, is confusing from another standpoint. A neutral color in ω space is one for which $\omega_1=\omega_3$

[1] P. Moon and D. E. Spencer, J. Opt. Soc. Am. **33**, 270 (1943).
[2] S. M. Newhall, D. Nickerson, and D. B. Judd, J. Opt. Soc. Am. **33**, 385 (1943).

$=0$. The origin in the $\omega_1\omega_3$ plane ($\omega_1=\omega_3=0$) is defined by the equations

$$\begin{aligned} p_1-0.95p_2&=0\\ p_2-1.10p_2&=0. \end{aligned} \tag{3}$$

If $Y=\alpha Y_0$, these equations become

$$\begin{aligned} \frac{x}{y}&=\left[\frac{x_0}{y_0}+0.95(\alpha-1)\right]\frac{1}{\alpha},\\ \frac{z}{y}&=\left[\frac{z_0}{y_0}+1.10(\alpha-1)\right]\frac{1}{\alpha}. \end{aligned} \tag{4}$$

From these equations it follows that

$$\begin{aligned} x&=\frac{x_0+0.95y_0(\alpha-1)}{1+3.05y_0(\alpha-1)},\\ y&=\frac{\alpha y_0}{1+3.05y_0(\alpha-1)},\\ z&=\frac{z_0+1.1y_0(\alpha-1)}{1+3.05y_0(\alpha-1)}, \end{aligned} \tag{5}$$

from which the chromaticity of the origin can be calculated as a function of α or Y/Y_0. This was done for Illuminant C adaptation, with results as indicated in Fig. 1. The curve shows

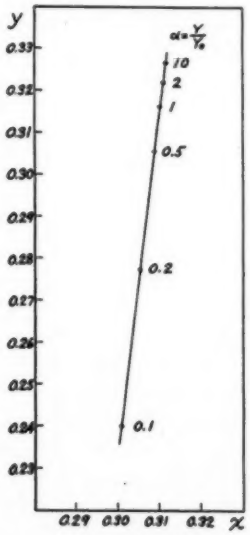


FIG. 1. I.C.I. chromaticity diagram showing change in position of the point $\omega_1=\omega_3=0$ for I.C.I. Illuminant C adaptation as a function of $\alpha=Y/Y_0$.

the chromaticity necessary for a color to appear neutral as a function of the relative values of Y and Y_0. Only when $Y=Y_0$ does the origin have the same chromaticity as the adaptation, which is the trivial case for a color identical with the adaptation.

If it be required that the chromaticity of the origin coincide with that of the adaptation for all values of Y, then setting $x=x_0$, $y=y_0$, and $z=z_0$ in Eqs. (5) yields the conditions

$$x_0=0.95y_0 \quad \text{and} \quad z_0=1.1y_0. \tag{6}$$

These conditions require that the chromaticity of the adaptation be given by

$$\begin{aligned} x_0&=0.3115,\\ y_0&=0.3279,\\ z_0&=0.3606. \end{aligned} \tag{7}$$

If Y_0 be taken as 20, then $X_0=19$ and $Z_0=22$. These results also follow immediately from Eqs. (3).

This adaptation has a dominant wave-length of 557 mμ, and an excitation purity of 3.6 percent. It is unique in being the only adaptation for which colors of the same chromaticity as the background fall at the origin in the $\omega_1\omega_3$ plane for all values of Y/Y_0. On the other hand, this adaptation is subject to the criticism mentioned above concerning the lack of agreement between dominant wave-length and hue in ω space for near neutral colors. This adaptation was chosen here for the study of the ω space because the prospect of an origin of variable chromaticity appeared to be more confusing than the lack of correlation of hue and dominant wave-length for the nearly neutral colors.

THE I.C.I. TO ω TRANSFORMATION

If $X_0=0.95Y_0$ and $Z_0=1.1Y_0$, then Eqs. (1) become

$$\begin{aligned} \omega_1&=\frac{X-0.95Y}{0.084Y_0(0.63+Y/Y_0)^{\frac{1}{2}}-0.0595Y_0},\\ \omega_3&=\frac{(Z-1.1Y)^{1.2}}{0.2768Y_0^{1.2}(0.8+Y/Y_0)^{\frac{1}{2}}-0.2296Y_0^{1.2}}. \end{aligned} \tag{8}$$

For colors for which Y is approximately equal to Y_0, the scale of ω_1 varies as $1/Y_0$ and that of ω_3 as $1/Y_0^{1.2}$. There is thus some change in the

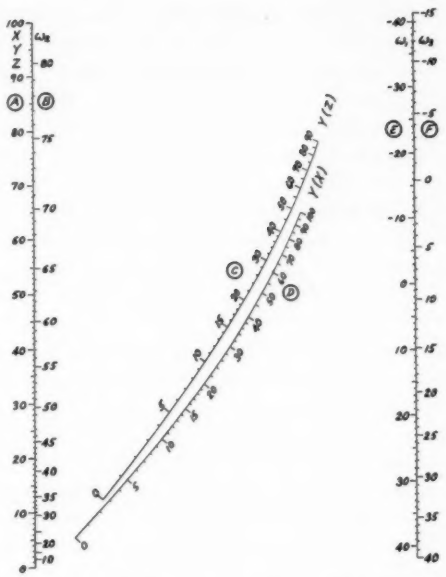


FIG. 2. Simplified nomographs for making the transformation from X, Y, Z, to ω_1, ω_2, ω_3, and vice versa. Find X on scale A, Y on scale D, and with a straightedge read ω_1 on scale E. Find Z on scale A, Y on scale C, and read ω_3 on scale F. Find Y on scale A and read ω_2 on scale B.

relative magnitude of ω_1 and ω_3 with a variation in Y_0, and for colors for which Y is quite different from Y_0 the change is still more complicated. It is evident, however, that the choice of Y_0 is not critical, and we have arbitrarily chosen $Y_0=20$.

With $Y_0=20$, the equations become

$$\omega_1=\frac{X-0.95Y}{0.3757(12.6+Y)^{\frac{1}{3}}-1.19},$$
$$\omega_3=\frac{(Z-1.1Y)^{1.2}}{2.253(16+Y)^{\frac{1}{3}}-8.36}. \qquad (9)$$

These equations are represented by nomographs in Fig. 2, which shows simplified forms of the nomographs used to facilitate the transformation between I.C.I. notation and the ω space for the calculations given in this paper.

The relation given by Moon and Spencer for the second coordinate, namely,

$$\text{Value}=5.0(p_2+1)^{0.426}, \qquad (10)$$

or,

$$\omega_2=41.7(p_2+1)^{0.426}, \qquad (11)$$

which now becomes

$$\omega_2=11.64\,Y^{0.426} \qquad (12)$$

for $Y_0=20$, was found to give considerable distortion at Munsell values between 1 and 2. For value 1, the recommended Y is 1.210, but Eq. (10) gives value = 1.515 for $Y=1.210$. A much better fit with the recommended values is given by the equation

$$\text{Value}=6.58(p_2+1)^{0.343}-1.52, \qquad (13)$$

or, for $Y_0=20$,

$$\text{Value}=2.357\,Y^{0.343}-1.52, \qquad (14)$$

so that

$$\omega_2=19.62\,Y^{0.343}-12.5. \qquad (15)$$

Equation (15) was used in this paper, but one could well use directly a curve of value *vs.* Y as given by the data of Newhall *et al.*,[2] since the object is to obtain as good a fit as possible with the recommended values. A comparison of Eqs. (10) and (13) is shown in Fig. 3.

DOMINANT WAVE-LENGTH AND HUE ANGLE θ

It is interesting to consider the transformation of straight lines in the $\omega_1\omega_3$ plane (constant hue) to the I.C.I. chromaticity diagram (Fig. 4). For a straight line in the $\omega_1\omega_3$ plane, $\omega_3/\omega_1=\tan^{-1}\theta=\beta$, a constant. Use of Eqs. (9) gives the relation

$$\frac{(1-x-2.1y)^{1.2}}{x-0.95y}=\beta F(Y)\left(\frac{y}{Y}\right)^{0.2}, \qquad (16)$$

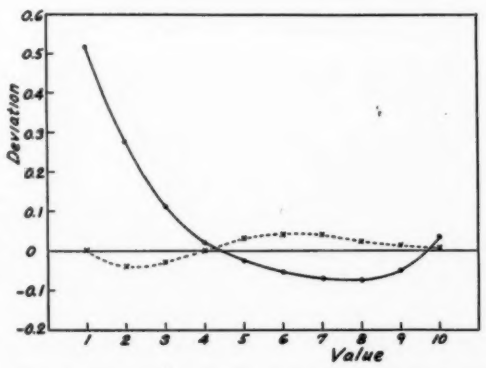


FIG. 3. Comparison of Eqs. (10) [solid line] and (13) [dotted line], showing deviations from the recommended Munsell value in units of one value step when the recommended Y for Munsell values from 1 to 10 is used in the two equations.

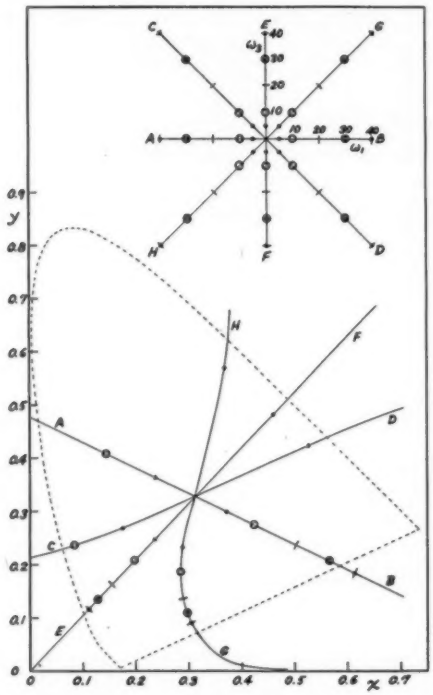


FIG. 4. Transformation of constant hue lines in the $\omega_1\omega_3$ plane to the I.C.I. chromaticity diagram. Points were calculated for $Y=10$.

where

$$F(Y)=\frac{2.253(16+Y)^{\frac{1}{3}}-8.36}{0.3757(12.6+Y)^{\frac{1}{3}}-1.19}.$$

If $\omega_3/\omega_1=0$, or $\beta=0$ (line AB), Eq. (16) becomes

$$1-x-2.1y=0,$$

so that the straight line AB transforms over into another straight line on the chromaticity diagram. This line has a slope $-1/2.1$ and passes through the point $x=1$, $y=0$. The line is the same for any Y, although the position along the line corresponding to any particular value of ω_1 depends upon Y. Similarly, the line $\omega_1/\omega_3=0$, or $\beta=\infty$ (line EF), transforms into the straight line

$$x-0.95y=0,$$

which passes through the origin.

All other straight lines of the equation $\omega_3/\omega_1=\beta$ become curved lines in the xy diagram, since Eq. (16) is not linear. Furthermore, the transformed line is a function of Y. This transformation has been studied in detail by the authors, but only several general remarks will be given here. It can be shown that all radial lines in the first quadrant go through the point $x=1$, $y=0$. Radial lines in the other three quadrants show less curvature. The y axis when transformed to the $\omega_1\omega_3$ plane becomes a straight line parallel to the ω_3 axis, with ω_1 negative and a function of Y.

Comparison of Fig. 4 with Fig. 13 of reference 2 is interesting. Some cases of qualitative agreement are to be found and some cases of disagreement. The straight line AB, for instance, is in approximately the same position as some of the lines of $10G$ and $10RP$, which show considerable curvature. The curved line OG comes near to the position where the nearly straight $5P$ and $7.5P$ lines lie. Lines between OG and OB would have the opposite curvature to the lines of the hues between $10P$ and $10RP$. The straight line EF would correspond approximately to $5PB$ and $5Y$, both of which show only moderate curvature. The lines OD and OH appear to be curved in the proper direction, whereas the line OC is curved oppositely to $10BG$.

CONSTANT VALUE PLANES

The data given by Granville, Nickerson, and Foss[3] for the tristimulus values of the 100

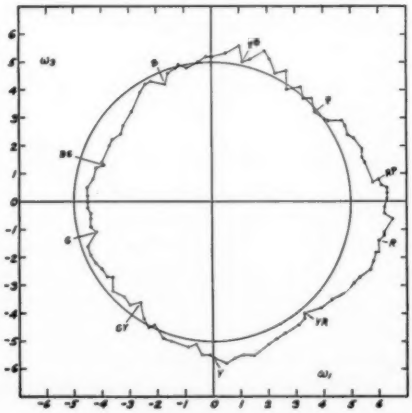


FIG. 5. The Munsell 100 hue circle plotted in the $\omega_1\omega_3$ plane.

[3] W. C. Granville, D. Nickerson, and C. E. Foss, J. Opt. Soc. Am. **33**, 376 (1943).

Munsell hues at value 5 were plotted in the $\omega_1\omega_3$ plane (Fig. 5) in order to investigate the spacing of the hues. According to the ω space representation, the reds are too saturated and the greens and blues somewhat too weak. The colors are quite evenly distributed among the four quadrants. In Fig. 6, Munsell hue is plotted against the hue angle θ. The largest deviations from the straight line occur for the blues and purples. The straight line corresponds to that given by Moon and Spencer for the angular spacing of the hues.

In Fig. 7 the Munsell colors of value 5 for 40 hues and all chromas have been plotted from the data given by Kelly, Gibson, and Nickerson[4] and by Granville, Nickerson, and Foss.[3] To compare with the data of the actual colors shown in Fig. 7, the recommended positions[2] for the Munsell colors of value 5 have been plotted similarly in Fig. 8. The latter figure indicates that the smoothing process has been quite successful in this plane. The most striking feature of Fig. 8 is the disagreement between the recommended colors and the ω space as far as saturation is concerned, or distance from the origin. The first few innermost chroma contour lines, which were used by Moon and Spencer in deriving the ω transformation, can be approximated fairly well by circles. At higher chromas,

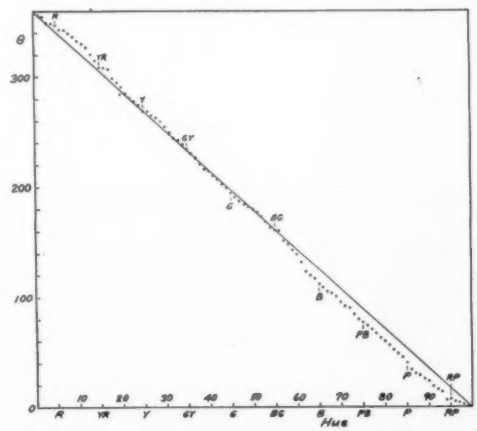


FIG. 6. Colors of the Munsell 100 hue circle, showing the correlation between the Munsell hue number and the hue angle θ from Fig. 5.

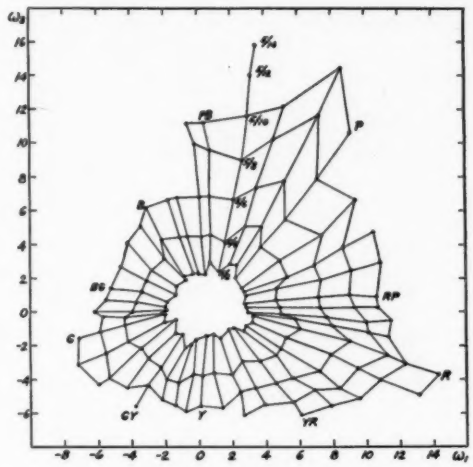


FIG. 7. The Munsell colors of value 5.

however, the deviations from the ideal circles become serious. As indicated by the following figures in this paper, the same general distortion is maintained at all values.

It must be realized that some of the data of Fig. 8 at the higher chromas are based upon extrapolation beyond the actual Munsell colors and therefore beyond the experimentally observed data. Thus, while the discrepancy in this respect between theory and the recommended data is large, additional experimental data are needed before deciding in favor of either viewpoint. In this laboratory, a number of pigmented plastic samples of hue near 5*PB* were made up in a series of increasing chroma, spaced so as to represent equal steps in ω space. It was evident from this series that the colors at the higher chromas were considerably closer together visually than those at lower chromas, and that colors chosen to correspond to equal chroma steps based on the recommended Munsell data were much more satisfactory in respect to equal visual spacing. The series of plastic samples used extended out in chroma to 5/14 (recommended notation). Colors of this purity are not uncommon in the plastics industry, and they have considerable commercial importance. Thus a comparison of the theory with the extrapolated data is necessary, and in view of the differences illustrated in Fig. 8, additional experimental data are required. Whereas the authors are

[4] K. L. Kelly, K. S. Gibson, and D. Nickerson, J. Opt. Soc. Am. **33**, 355 (1943).

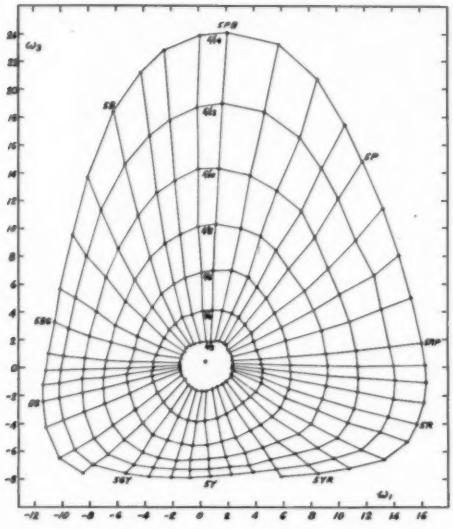


FIG. 8. The recommended positions of the Munsell colors of value 5.

convinced that in the case of purple blues, the spacing of the extrapolated data is much better than the spacing given by the theory, they have as yet no basis for a preference in the case of other hues, particularly yellows. It should also be pointed out that in the case of the colors of hue 7.5*PB*, the chromas 12 and 14 do not represent a very large extrapolation, since the experimental Munsell color 7.5*PB*5/14 is given a recommended notation of 7.0*PB*5.0/10.8, and the color 7.5*PB*4/16 is given the notation 7.0*PB*4.2/12.9. Thus chromas up to 11 (and 13 at value 4) are based upon experimentally observed data. Other hues should be investigated at higher chromas, but in the opinion of the authors, the chroma distortion of Fig. 8 is the most serious limitation to general use of the ω space at present.

CONSTANT HUE PLANES

The ω space may be represented by cylindrical coordinates, with

$$\omega_2/\omega_1 = \tan^{-1}\theta, \qquad \omega_1^2+\omega_2^2=\rho^2. \tag{17}$$

If the approximation is made that all Munsell colors of the same hue have a constant θ, then the colors of one hue can be plotted on the $\omega_2\rho$ plane. An idea of the validity of this approximation can be obtained from Fig. 8.

The Munsell colors of 5*R*, 5*B*, and 5*GY* have been plotted in this manner in Figs. 9–11. The positions of the recommended colors[2] are indicated by the small dots and the actual colors[3,4] by the circles. This manner of presentation illustrates the spacing of the colors of one hue to advantage. Some of the irregularities evident in Figs. 9–11 suggest that most of the smoothing of the Munsell colors was done on chromaticity diagrams of one kind or another, which accounts for the regularity of Fig. 8.

Some of the same trends are evident in these figures as in Fig. 8. For example, the reds spread out slightly with increasing chroma, the blues spread out considerably, and the spacing of the green yellows decreases at higher chroma. These same trends, in general, persist at all values, and probably are the result of a distortion produced by the ω transformation. In Fig. 11 (green yellows), the spacing between the chromas increases with the value. This may or may not be a real departure of the Munsell recommendations from equal spacing. The local irregularities exhibited in the figures appear to be real deviations from ideal spacing. For example, the entire red chroma series of value 3 are too saturated, and this can be verified by plotting the original

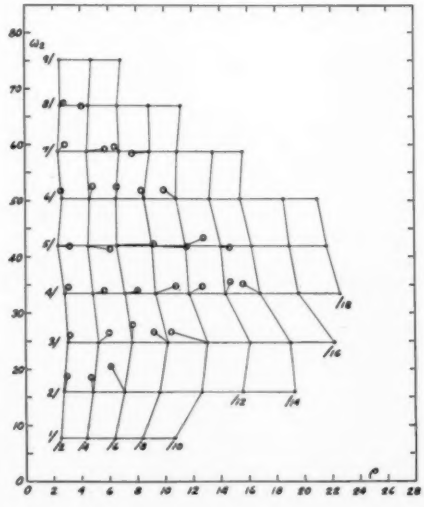


FIG. 9. Munsell colors of hue 5*R* and the recommended positions plotted in a constant hue plane.

data as given in I.C.I. notation. It would seem that the $\omega_2\rho$ plane would be of considerable assistance in smoothing the Munsell colors, to be used in addition to smoothing in the plane of constant value.

CONCLUSION

A method for comparing colors on a mathematical basis, such as is attempted by Moon and Spencer in their ω space, has important applications from the industrial standpoint in the field of color. Such a method would be useful for the specification of color tolerances, color differences, and color changes. The same method would be applicable to all colors, and one could tell, for example, whether two yellows were closer together than two blues.

The ω space does not appear to be a sufficiently accurate mathematical description of the Munsell color space to deserve wholehearted acceptance for some purposes by colorists in industry. The distortion mentioned above at the higher chromas is too serious to ignore. For example, the distance between $5GY5/6$ and $5GY5/8$ is about 3 chroma units. Greater discrepancies can be found. It must be emphasized that these discrepancies are between the theory and the recommended Munsell data, and not necessarily between theory and the ideal equally-spaced color solid. This is a question which cannot be answered without additional experimental data in the region of the extrapolated chromas. As mentioned above, in the case of purple blues the authors believe that the theory is at fault.

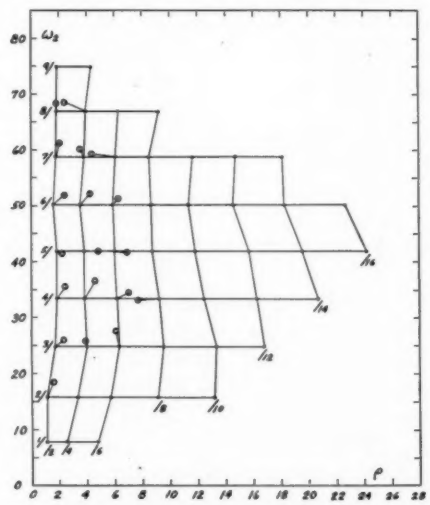


FIG. 10. Munsell colors of hue 5*B* and the recommended positions.

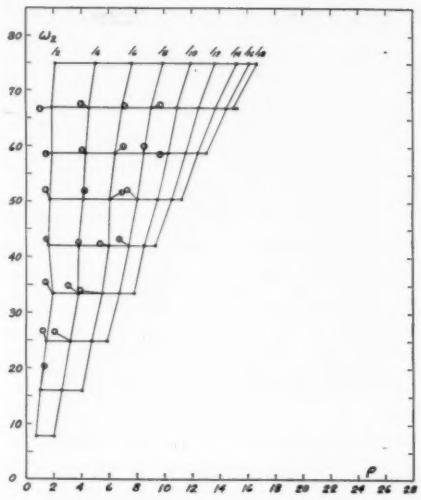


FIG. 11. Munsell colors of hue 5*GY* and the recommended positions.

Another point which appears to require more attention is that concerning the relation between a chroma change and a value change, or the scale of ω_2 relative to that of ω_1 and ω_3. No work on this problem has been done in this laboratory, but visual inspection of the Munsell colors has led us to believe that the scale of ω_2 is too large. Accordingly, Figs. 9–11, have been plotted with the scale of ω_2 reduced by 2/5 compared to that of ρ. This figure for the scale of ω_2 relative to that of ω_1 and ω_3 is not recommended, but it appears to be a reasonable value. The question should be further investigated.

American Standard Definition of Safety Photographic Film—Z38.3.1–1943*

FOREWORD

THE American Standard Definition of Safety Photographic Film defines a photographic film which is no more hazardous than common newsprint paper. In order to be classified as Safety Photographic Film, a photographic film must (*a*) be difficult to ignite, (*b*) be slow burning, and (*c*) evolve a limited amount of toxic oxides of nitrogen during decomposition.

The ease of ignition is determined by measuring the time of ignition after subjecting the sample to a uniformly maintained high temperature. The requirement for ease of ignition and the test method are the same as those specified by the British Standard Definition of Cinematograph "Safety" Film (1939) and other European standards for safety motion picture film.†

The rapidity of burning and the method of measuring that characteristic are also the same as specified in the British Standard Definition of "Safety" Film (1939).*

The toxic gases evolved when photographic films of cellulose nitrate are decomposed by heat are oxides of nitrogen, carbon monoxide, and hydrocyanic acid. Laboratory tests made available to the committee indicate that only oxides of nitrogen and carbon monoxide are evolved in sufficient quantities to constitute an appreciable hazard. These tests also indicate that photographic film does not evolve more carbon monoxide than does common newsprint paper when equal quantities of film and paper are decomposed in the same manner.

The maximum quantity of oxides of nitrogen which can evolve when safety photographic film decomposes is limited by stipulating in the definition the maximum nitrogen (present as nitrate) content of the material. Fumes from photographic film that comply with this standard will not be significantly different from fumes evolved from ordinary newsprint paper decomposed under the same conditions.

Photographic films made from materials for which this definition applies but which do not comply in one or more respects are not necessarily hazardous. For example, acetate film may fail to comply with the maximum nitrogen content specified in this definition and still not be significantly more hazardous than common newsprint paper under ordinary conditions.

The committee considered a maximum nitrogen content of 0.72 percent and had some evidence that a safety film containing that proportion of nitrogen was no more toxic than films with a lower content. However, the specification was set at a lower figure to correspond with the current requirements of the Underwriters' Laboratories. The method for measuring the nitrogen content was adopted from the Summary of *Requirements for Slow Burning Cellulose Acetate Film*, Underwriters' Laboratories, Inc., Chicago, Illinois.

The definition of Safety Photographic Film applies only to films, the supports for which comprise cellulose esters of simple fatty acids, combinations of cellulose esters and nitrate, and regenerated cellulose. Should photographic films in the future be made of other materials, this definition may have to be modified and additional requirements incorporated in the definition.

Suggestions for improvement based upon experience gained in the use of this definition will always be welcome. They should be sent to the American Standards Association, 29 West 39 Street, New York 18, New York.

The American Standards Association in the past has acted as the secretariat for the project on Photography, ISA 42 of the International Standards Association. A printed draft of this standard, dated December 1, 1940, was circulated for comments to those countries holding membership in ISA Committee 42 and also to the International Congress of Scientific and Applied Photography, which also participates.

The ASA Committee on Standardization in the Field of Photography was initiated in September, 1938, on the recommendation of a general conference of the American photographic industry following a request from the International Standards Association that the ASA accept the

* Approved June 11, 1943. Sponsor: Optical Society of America.

† These requirements were proposed at the Eighth Congress of International Photography at Dresden in 1931 (*Bericht über den VIII. Internationalen Kongress für Wissenschaftliche und Angewandte Photographie*, pp 279–286) and adopted by the Ninth Congress, Paris, 1935 (see *IX^e Congress International de Photographie*).

secretariat for ISA Committee 42 on Photography. The Optical Society of America was designated as sponsor for the ASA project.

The scope for the ASA project is as follows:

> The formulation of definitions, dimensional standards, and recommended practices in the field of photography, and the establishment of methods for testing, rating, and classifying the performance characteristics of materials and devices used in photography, including its industrial applications, but excluding cinematography.

The membership of the ASA Committee on Standardization in the Field of Photography, Z38, is as follows:

LOYD A. JONES, *Chairman*
J. W. MCNAIR, *Secretary*

Organization Represented	*Name of Representative*
Optical Society of America (*Sponsor*)	RAYMOND DAVIS C. W. GARTLEIN A. C. HARDY LOYD A. JONES BRIAN O'BRIEN
Agfa Ansco—Division of General Aniline & Film Corporation	PAUL ARNOLD JOHN FORREST
American Astronomical Society	FRED L. WHIPPLE
American Chemical Society	S. E. SHEPPARD
American Committee of the International Congress of Photography	WALTER CLARK
American Geophysical Union	CAPTAIN T. J. MAHER
American Microscopical Society	OSCAR W. RICHARDS
American Optical Company	E. D. TILLYER O. W. RICHARDS (*Alt*)*
American Roentgen Ray Society	FRED O. COE, M.D.
American Society of Photogrammetry	O. M. MILLER
American Society for Testing Materials	L. V. FOSTER H. E. SEEMANN (*Alt*)
Bausch & Lomb Optical Company	W. B. RAYTON L. V. FOSTER (*Alt*)
Biological Photographic Association	LOUIS SCHMIDT LEO C. MASSOPUST (*Alt*)
Cambridge Instrument Company, Inc.	U. O. HUTTON
Defender Photo Supply Company, Inc.	ROWLAND S. POTTER A. D. JACKLING (*Alt*)
DuPont Film Manufacturing Corporation	D. R. WHITE
Eastman Kodak Company	F. M. BISHOP V. J. MOYES (*Alt*) M. E. RUSSELL WALTER CLARK (*Alt*)
Electrical Testing Laboratories	S. MCK. GRAY
Fairchild Aerial Camera Corporation	GEORGE RATTRAY IRVING DOYLE (*Alt*)
Folmer Graflex Corporation	GAYLORD C. WHITAKER V. E. WHITMAN (*Alt*)
Gevaert Company of America, Inc.	JOSEPH H. COENEN
Haloid Company	JOHN DESSAUER
Interchemical Corporation	GEORGE WELP
International Industries, Inc.	C. H. HARRIS W. A. PATTON (*Alt*)
E. Leitz, Inc.	AUGUSTUS WOLFMAN
Lithographic Technical Foundation, Inc.	PAUL W. DORST
National Bureau of Standards, U. S. Department of Commerce	RAYMOND DAVIS
National Electrical Manufacturers' Association	J. S. COWLES W. N. GOODWIN, JR. F. K. MCCUNE
National Photographic Dealers' Association	H. O. BODINE
Photo Utilities, Inc.	JOSEPH M. BING WALTER J. ARCHINAL (*Alt*)
Photographers' Association of America	WILLIAM GERDES
Photographic Society of America	JOHN R. WEBER F. QUELLMALZ, JR. (*Alt*)
Radiological Society of North America	F. O. COE, M.D.
Society of Motion Picture Engineers	J. I. CRABTREE
Underwriters' Laboratories, Inc.	A. F. MATSON
U. S. Department of Commerce, Coast and Geodetic Survey	COMMANDER O. S. READING CAPTAIN T. J. MAHER (*Alt*)
U. S. Navy Department	Bureau of Aeronautics, Photographic Section, Officer-in-Charge
U. S. War Department—Air Corps	GEORGE A. MAGNUS
U. S. War Department—Signal Corps	CAPTAIN ROBERT F. NICHOLSON
Universal Camera Corporation	GEORGE KENDE.

* *Alt*—abbreviation for alternate.

Subcommittees have been appointed to develop standards, specifications, and methods of test under the above broad scope which covers the whole photographic field. The assignments of the subcommittees are as follows:

Subcommittee 1—Physical dimensions of sensitive materials, specifically of unexposed, unprocessed, sensitive materials and holders therefor.
Subcommittee 2—Sensitivity to radiant energy.
Subcommittee 3—Supports for sensitive coatings.
Subcommittee 4—Exposing equipment: cameras, lenses, shutters, etc.
Subcommittee 5—Photographic characteristics of illuminants.
Subcommittee 7—Printing and projection equipment.
Subcommittee 8—Processing and processing equipment.
Subcommittee 9—Definitions: abbreviations and symbols; form and arrangement of published standards; numbering of standards.

The Subcommittee on Supports for Sensitive Coatings, Subcommittee No. 3, which developed this standard definition of safety photographic film, has the following personnel:

R. F. NICHOLSON, *Chairman*

PAUL ARNOLD	L. V. FOSTER
E. K. CARVER	JOHN R. HILL
F. O. COE	A. F. MATSON
RAYMOND DAVIS	S. E. SHEPPARD.

0. SCOPE

Photographic films are classified as safety photographic film if they are difficult to ignite, slow burning, and low in nitrogen content.

1. IGNITION TIME

1.1 Definition. Film supports for light-sensitive materials are classified as difficult to ignite when the ignition time is greater than ten minutes.

1.2 Method of Measurement. The ignition time of photographic films is measured as follows:

1.2.1 ***Sample.*** A sample 35 mm long and 8 mm wide shall be cut from the film to be tested. The sample shall be free of perforations as far as is practicable. All gelatin layers shall be removed by washing in warm water, and the sample shall then be dried for at least 12 hours by being suspended freely in air having a temperature of 18 C to 22 C and a relative humidity of 40 to 50 percent.

1.2.2 ***Procedure.*** The test shall be made in an electric resistance oven, the interior of which shall be in the form of a vertical cylinder (preferably with a rounded bottom), having a diameter of 70 mm and a mean height of 70 mm. The top of the oven shall be closed by means of a closely overlapping lid, having two holes of 7 mm and 15 mm, respectively, the centers being at a distance of about 15 mm from each other. A thermocouple shall be introduced through the smaller opening, the connecting wires having a porcelain coating fitting tightly into the hole. Alternatively, the temperature in the cylinder may be measured by means of a mercury thermometer, protected from rising heat by means of a cork disk lying a little above the lid.

1.2.3 ***Temperature.*** The oven shall be brought to, and maintained at, a temperature of 300° C ±3° C. When this temperature is reached, the sample, attached to a thin U-shaped wire hook, shall be introduced through the larger opening. The thermocouple (or the thermometer) and the sample shall be fixed in such a way that the thermojunction (or the mercury bulb) and the center of the sample shall be at an equal depth of about 35 mm.

1.2.4 ***Time Interval.*** The time interval from the insertion of the sample to the ignition of the sample is recorded as the ignition time.

1.2.5 ***Preparation for Tests.*** Between tests, the oven shall be thoroughly aired.

2. BURNING TIME

2.1 Definition. Photographic films having a thickness equal to or greater than 0.08 mm are classified as slow burning when the burning time is not less than 45 seconds. Photographic films having a thickness less than 0.08 mm are classified as slow burning when the burning time is not less than 30 seconds.

2.2 Method of Measurement. The burning time of photographic films is measured as follows:

2.2.1 ***Sample.*** A sample 35 cm long and 35 mm wide shall be cut from the film to be tested. All gelatin layers are to be removed by washing in warm water. The sample shall then be dried for at least 12 hours by being suspended freely in air having a temperature of 18° C to 22° C and a relative humidity of 40 to 50 percent.

The sample shall be marked at a point 5 cm from one end. The sample shall be perforated with holes 3 mm in diameter along both edges. Perforations are to be at intervals of not more than 32 mm.

2.2.2 ***Procedure.*** A wire having a diameter of not more than 0.5 mm shall be threaded through the perforations on one side so that the sample is supported at points not more than 32 mm apart. With the wire stretched horizontally and the sample hanging vertically from it, the bottom corner of the marked end is to be ignited.

2.2.3 ***Time Interval.*** The time which elapses from the moment the flame reaches the mark until the sample is completely burned shall be recorded as the burning time. If the sample does not ignite or if it does not completely burn, the burning time is recorded as infinity.

2.2.4 ***Test Conditions.*** The test shall be made in a room free from draughts and immediately after the period of drying. At least three tests shall be made.

3. NITROGEN CONTENT

3.1 Definition. Photographic films having a nitrogen content less than 0.36 percent by weight are classified as having a low nitrogen content.

3.2 Method of Measurement. The nitrogen content of photographic films is measured as follows:

3.2.1 ***Sample.*** After the emulsion is removed, 2.5 grams of support are cut into small pieces and

placed in an 800-cc Kjeldahl flask. To this are added 90 cc of 30-percent sodium hydroxide and 10 cc of ethyl alcohol. (Note 1.) The sample may be conveniently held overnight at this point.

3.2.2 ***Procedure.*** The sample is heated on the steam bath, and 25 cc of 30 percent hydrogen peroxide are added slowly, followed by agitation with a stirring rod. When the first portion of hydrogen peroxide is boiled out, another 20-cc portion is added; this is usually sufficient to dissolve the support completely. When the reaction has ceased, the stirring rod is removed and washed down with distilled water. The contents of the flask will now be approximately 200 cc.

3.2.3 ***Temperature.*** The solution is evaporated over a flame to 75–100 cc volume to remove the last traces of ammonia, diluted to a total of 350 cc with distilled water, cooled, and immediately before connecting the flask to the Kjeldahl apparatus, 2.5 grams of DeVarda's alloy are added quickly. After the flask is connected, about 200 cc of distillate are collected in a 500-cc Erlenmeyer flask containing 50 cc of standard tenth-normal sulfuric acid. The excess acid is back titrated with tenth-normal alkali. (Note 2.)

3.2.4 ***Method of Calculation.*** A blank determination is made on the reagents, using the same quantities that are used in the actual determination. The percent nitrate nitrogen in the sample is calculated as follows:

$$\frac{[(\text{cc acid in blank}) - (\text{cc acid in sample})] \times 0.1 \times 0.014 \times 100}{2.5} = \text{percent nitrogen.}$$

NOTE 1. Ethyl alcohol denatured with CP methyl alcohol may be used.

NOTE 2. Three sources of error must be avoided in this test:

(*a*) When evaporating the solution following the peroxide digestion, mechanical loss by entrainment may occur if the solution is boiled down too far. This will give low results.

(*b*) When distilling the sample after addition of the DeVarda's alloy, some alkali may be carried over into the standard acid by entrainment if the distillation is carried too far, or is too vigorous. This will give high results.

(*c*) The total volume of the sample at the time of addition of the DeVarda's alloy must be closely controlled. Too much or too little water added changes the alkali concentration so that the rate of reaction with the alloy and the corresponding reduction of the sodium nitrate present will be erratic.

American Standard Lens Aperture Markings—Z38.4.7–1943*

1. The symbol for relative aperture of a lens shall be *f*/ followed by the numerical value of the quotient of the focal length divided by the effective aperture, as in the example *f*/8. Where preferable, the symbol *f*: may be used.

2. The measured diameter of the maximum aperture, as seen from the front of the lens, shall be at least 95 percent of the quotient obtained on dividing the engraved focal length by the engraved *f*-number.

3. The standard series of diaphragm markings shall be *f*/0.7, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, 128.

4. The maximum relative aperture marked on a lens need not be selected from the above series but should be followed by the above series of stop openings beginning with the next larger number whenever practical and progressing as far as required in the individual application. Example: An *f*/1.9 lens might be engraved *f*/1.9, 2.8, 4, 5.6, 8, etc., if it were felt that to mark it *f*/1.9, 2.0, 2.8, 4.0, 5.6, etc., would confuse the markings at the *f*/1.9 end of the scale.

* Approved June 11, 1943 by American Standards Association. Sponsor: Optical Society of America.

American Standard Methods of Testing Printing and Projection Equipment—Z38.7.5–1943*

1. TEST FOR UNIFORMITY OF CONTACT BETWEEN NEGATIVE AND POSITIVE IN PRINTING EQUIPMENT

1.1 A test negative shall be made from an engraver's 120-line-per-inch screen in such a manner as to have alternating clear and opaque regions of equal area. The base material of the test negative shall be the same (i.e., film or glass) as the base material of the negative to be used in the equipment being tested. A contact print of the test negative shall be made on photographic paper. Any departure from a uniform gray tone in the print indicates poor contact.

2. MEASUREMENT OF FILM OR SLIDE TEMPERATURE

2.1 A thermocouple of No. 38 or 39 Brown and Sharpe gauge wire shall be held in contact with the test film at the center of the maximum aperture standard for the given nominal size being tested, and the rise in degrees centigrade above room temperature determined with an instrument accurate to $\pm 2°$ C. The test film shall be of uniform density of 2.0 or greater. The thermocouple should be cemented to the test film or held in good contact with the film by being bound with it (as in a lantern slide) on the side of the test film away from the light source.

Film strip, lantern slide projectors, microfilm readers, and similar instruments shall be continuously operated for one hour with the test film in place, and the temperature rise measured at the end of this one-hour period.

3. MEASUREMENT OF THE UNIFORMITY OF ILLUMINATION OF THE SCREEN

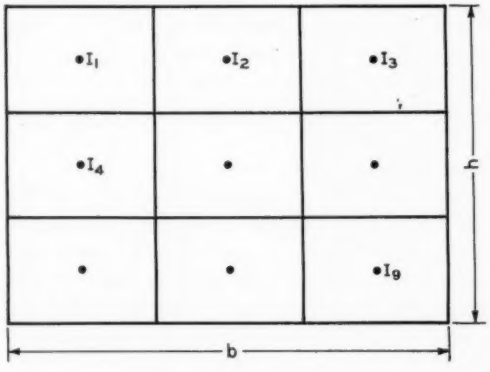
3.1 Focus on the screen a clear glass slide masked to the maximum aperture given in the standards for the nominal size being tested, and magnified to the arbitrary height (h) and width (b). The width shall be not less than 40 inches (1 meter). The slide shall be removed during measurement, but the other adjustments shall remain unchanged. The lamp of the projector shall be operated at its rated voltage.

3.2 The measuring equipment used shall have a precision of ± 5 percent. If a photoelectric cell is used, it shall have an attached filter to correct its sensitivity to that of human visibility for the different wave-lengths of light.

3.3 Corner-to-Center Ratio. Measurement shall be made at the center and at the four points in the corners, located 1/20 of the screen width from the top or bottom edge and the same distance from the side edges of the screen. The average illumination of the four corner points, divided by that of the center, and multiplied by 100, shall be the percentage of corner-to-center illumination.

3.4 Lumen Output. The screen image (3.1) is divided into nine equal areas as shown in the figure. The illumination I_n is measured at the center of each area in footcandles and h and b in feet.

$$\text{Screen Lumens} = \frac{hb}{9} \sum_{n=1}^{n=9} I_n$$



* Approved June 11, 1943 by American Standards Association. Sponsor: Optical Society of America.

Proposed American Standard Method of Processing for Sensitometry of Photographic Paper—Z38.2.3*

FOREWORD

SUBCOMMITTEE 2 of the American Standards Association Committee on Photography (Z38) has been considering for some time the problem of a useful method of processing for the sensitometry of photographic papers intended for projection or contact printing of continuous tone negatives. The proposed standard describes a procedure which it is felt will be found satisfactory as a standard method for exposing and processing photographic papers with a view to obtaining useful characteristic curves. This document is being published for a year's trial and criticism.

The method of obtaining the characteristic curve of papers has been set up according to much the same plan as was followed for the specification for determining the photographic speed of films (Z38.2.1-1943). An intensity scale exposure is made standard, followed by a processing technique intended to duplicate, as closely as possible, the practice met in actual commercial use of the material.

The committee has not had an opportunity to work out a satisfactory method of evaluating speed, contrast, scale, and other sensitometric constants from the characteristic curves. However, for many types of work the curves themselves are chiefly needed; hence the proposed method for obtaining the curves will be found useful as a standard. Later it is planned to add to the present specification a method of numerically evaluating the data obtained by the procedure.

Suggestions for improvement based upon experience gained in the use of this method will always be welcome. They should be sent to the American Standards Association, 29 West 39 Street, New York 18, New York.

The American Standards Association in the past has acted as the secretariat for the project on Photography, ISA 42 of the International Standards Association. A printed draft of this proposed standard, dated December 1, 1940, was circulated for comments to those countries holding membership in ISA Committee 42 and also to the International Congress of Scientific and Applied Photography, which also participates.

* Not approved. Sponsor: Optical Society of America.

The ASA Committee on Standardization in the Field of Photography was initiated in September, 1938, on the recommendation of a general conference of the American photographic industry following a request from the International Standards Association that the ASA accept the secretariat for ISA Committee 42 on Photography. The Optical Society of America was designated as sponsor for the ASA project.

The scope for the ASA project is as follows:

> The formulation of definitions, dimensional standards, and recommended practices in the field of photography, and the establishment of methods for testing, rating, and classifying the performance characteristics of materials and devices used in photography, including its industrial applications, but excluding cinematography.

The membership of the ASA Committee on Standardization in the Field of Photography, Z38, is given on p. 175 of this issue.

Subcommittees have been appointed to develop standards, specifications, and methods of test under the above broad scope which covers the whole photographic field. The assignments of the subcommittees are as follows:

Subcommittee 1—Physical dimensions of sensitive materials, specifically of unexposed, unprocessed, sensitive materials and holders therefor.
Subcommittee 2—Sensitivity to radiant energy.
Subcommittee 3—Supports for sensitive coatings.
Subcommittee 4—Exposing equipment: cameras, lenses, shutters, etc.
Subcommittee 5—Photographic characteristics of illuminants.
Subcommittee 7—Printing and projection equipment.
Subcommittee 8—Processing and processing equipment.
Subcommittee 9—Definitions: abbreviations and symbols; form and arrangement of published standards; numbering of standards.

The Subcommittee on Sensitivity to Radiant Energy, Subcommittee No. 2, which developed this proposed standard, has the following personnel:

M. E. RUSSELL, *Chairman*

PAUL ARNOLD
JOSEPH M. BING
WALTER CLARK
RAYMOND DAVIS
JOHN DESSAUER
W. N. GOODWIN, JR.
F. K. MCCUNE
BRIAN O'BRIEN
ROWLAND S. POTTER
E. D. TILLYER
D. R. WHITE.

0. SCOPE

This proposed method relates to the exposing and processing, for sensitometric purposes, of "metallic silver image" developing out photographic paper intended for projection or contact printing of continuous-tone picture negatives.

1. CONDITIONING OF THE SAMPLE BEFORE TESTING

The test sample shall be in equilibrium with an atmosphere maintained at a temperature of 20° C±5 degrees, and a relative humidity of 50±5 percent.

2. EXPOSURE

2.1 Type of Sensitometer. The sensitometer shall be a non-intermittent intensity scale type.

2.2 Exposure Time. Exposure time shall be 4 seconds.

2.3 Modulation. The change in exposure with distance along the test strip shall be not greater than a factor of 2 per 2 cm. Where stepped increments are used, the exposure increment shall be not greater than a factor of cube root of 2 per step.

2.4 Character of Light Incident on the Sample. The light incident on the test sample shall be that from a tungsten filament incandescent lamp operated to produce a spectral quality with an energy distribution corresponding to a color temperature of 2800 Kelvin±15 degrees.

3. PROCESSING

3.1 Developing Solution

Water (about 125° F)	500 cc
Metol	3.1 grams
Sodium sulfite (anhydrous)	45.0 grams
Hydroquinone	12.0 grams
Sodium carbonate (desiccated)	67.5 grams
Potassium bromide	1.9 grams
Water to	1000 cc

For use, dilute 1 part of stock solution with 2 parts of water.

Fresh solution shall be used for each test, and 1 liter of developer should be used for processing not more than the equivalent of 280 square inches of test material.

3.2 Developing Technique. Development shall be carried out immediately after exposure in a manner equivalent to the following: During development the test specimens (sensitometric strips) shall be maintained in a horizontal plane by means of any device which will not interfere with them physically or chemically to such an extent as to influence perceptibly the final sensitometric result. Development shall be carried out in a horizontal 11×14 in. tray containing 2 liters of developer. During development the developer shall be agitated to an extent equivalent to that provided by rocking the tray at a rate of 7½ complete cycles per minute (cycle: one motion in each of four directions; such agitation or rocking of the tray may be facilitated by using a block, 2½×2 in., ¾ in. high, under the tray center, long dimension parallel to the long dimension of the tray).

3.3 Extent of Development. The temperature of the developing solution shall be maintained at 20° C±0.5 degrees. Extent of development cannot be specified until the ultimate use of the data has been decided.

3.4 Acid Stop Bath. When the development has been completed, the sensitometric strips are removed from the developer and immediately immersed in the following acetic acid stop bath:

Acetic acid 28 percent	45 cc
Water to make	1 liter.

3.5 Fixing. After 1 minute in the acetic acid rinse bath, the sensitometric strips should be removed and transferred to the following fixing bath and occasionally agitated until fixing has been completed.

Water	2 liters
Sodium thiosulfate	480 grams
Hardener	
Water	160 cc
Sodium sulfite	30 grams
Acetic acid 28 percent	96 cc
Potassium alum	30 grams.

The temperature of the solution shall be maintained at 20° C±5 degrees, and the time of fixing shall be approximately 10 minutes.

3.6 Washing. The samples shall be washed for 15 minutes in running water at a temperature not

in excess of 25° C, or in 6 changes of water, allowing 5 minutes between each change.

3.7 Drying. The samples shall be air dried at a temperature not in excess of 40° C.

4. MEASUREMENT IN DENSITY

The sample should be illuminated at an angle of 45 degrees to the surface and the density measured normal to the surface. Samples having a pronounced surface characteristic should have the densities read first in one position perpendicular to the viewing axis. Then the specimen should be rotated through an angle of 90 degrees about the viewing axis and the density measured again. The two values thus obtained should be averaged and recorded as the density for that measurement.

Book Review

The Optical Properties of Organic Compounds.

ALEXANDER N. WINCHELL. Pp. 342+xiii; Figs. 157 (with folded determinative chart). The University of Wisconsin Press, Madison, Wisconsin, 1943. Price $5.00.

This book lists the optical crystallographic properties of nearly one thousand crystalline organic compounds. The data are fairly complete and are drawn principally from the literature over the period 1858–1941, although there is evidence of original work by the author and his assistants and critical evaluation of conflicting data. Private communications from many prominent workers in the field and the unpublished bibliographical thesis of H. W. Hartline (M.I.T., 1931) supplement the material gleaned from some four hundred references to the literature.

The material is organized in much the same way as in the author's classic *Microscopic Characters of Artificial Minerals*, namely, the arrangement of compounds according to chemical composition followed by tables based on refringence and a chart of refringence *vs.* birefringence. In the first tabulation the Beilstein system is used as the basis of classification and is accompanied by an alphabetical index. This scheme is to be commended although it relegates the many complex natural products listed to an organizational scrap heap. Thus "squash-seed globulin" is found between oxydehydrodeguelin and helenalin. The rules of nomenclature of the International Commission have been followed as far as possible, with trivial names and synonyms being given in most cases. Structural formulae are regrettably but reasonably restricted to the simpler compounds.

The determinative tables are based on refringence and each entry is accompanied by a page reference to the first or descriptive part of the book. The usual crystallographic and optical constants are given in most cases (system, axial ratio, habit, cleavage, D, $M.P.$, optic orientation, $2V$, refractive indices, birefringence). The determinative chart summarizes the information on refringence in a form adapted for quick identification, and the guide to the use of this chart is really an excellent summary of a simplified laboratory procedure which does not require observation of interference figures nor elaborate accessory equipment. This and the occasional listing of distinctive but not characteristic indices (N_1 and N_2) are of particular use to the worker with little or no experience in the field.

It is unfortunate that there is not more information on the solvents used in crystallizing the compounds listed and on the immersion media employed. The reviewer has known of several instances where potassium mercuric iodide and methylene iodide have apparently combined with the immersed sample and led to erroneous results for the refractive indices. Errors due to incipient dissolution of the sample are also encountered.

As a whole, the text is remarkably free from errors and evidently represents a great deal of painstaking work on the part of the author and his staff. The typography is characteristic of the printing process employed but the "typewritten" appearance is not objectionable.

The publication of this work is most timely, since it comes during a renaissance of interest in the possibilities of applying the optical crystallographic method to organic compounds. The availability of this excellent book will undoubtedly stimulate more widespread use of the method and, it is hoped, will also encourage the publication of much needed systematic data for various series of organic compounds and their common derivatives.

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